Teaching Aircraft Conceptual Design at the Undergraduate and Graduate Levels

Tony Hays
California State University Long Beach

This Presentation

- Review of textbooks and other supporting material
- Typical sequence of material to be presented in conceptual design course

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Aircraft Design Textbooks

- Raymer "Aircraft Design: A Conceptual Approach" 2012
- Nicolai and Carichner "Fundamentals of Aircraft and Airship Design" (two volumes) 2010
- Schaufele "The Elements of Aircraft Preliminary Design" 2007
- Gundlach "Designing Unmanned Aircraft Systems" 2012

Other Aircraft Design Textbooks

- Roskam “Airplane Design” (eight volumes) 1986
- Torenbeek “Synthesis of Subsonic Aircraft Design” 1982
- Obert “Aerodynamic Design of Transport Aircraft” 2009
- Jenkinson, Simpkin, Rhodes “Civil Aircraft Design” 1999
- Brandt, Stiles, Bertin, Whitford “Introduction to Aeronautics: A Design Perspective” 2004
- Fielding “Introduction to Aircraft Design” 1999

Other Aircraft Design Textbooks

- Corke “Design of Aircraft” 2002
- Sforza “Commercial Aircraft Design Principles” 2014
- Torenbeek “Advanced Aircraft Design” 2103
- Kundu “Aircraft Design” 2010
- Corning “Supersonic and Subsonic, CTOL and VTOL, Airplane Design” 1979
- Stinton “The Design of the Aeroplane” 1983

Other Aircraft Design Textbooks

- Küchemann “The Aerodynamic Design of Aircraft” 2012
- Loftin “Subsonic Aircraft: Evolution and the Matching of Size to Performance” 1980
- Whitford “Design for Air Combat” 1987
- Huenecke “Modern Combat Aircraft Design” 1987

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Countries That Don’t Use Metric System

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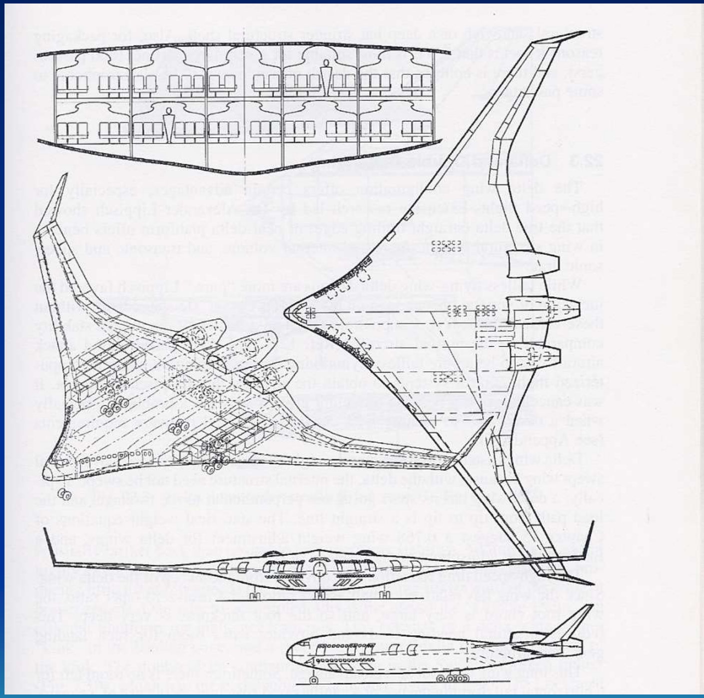
Blended Wing-Body

- Advantages
  - Higher L/D
  - Noise shielding of jet engines
- Disadvantages
  - Increased weight of non-cylindrical passenger cabin
  - Difficult passenger access/egress



Source: Raymer

Moller Skycar

- Moller International founded in 1983

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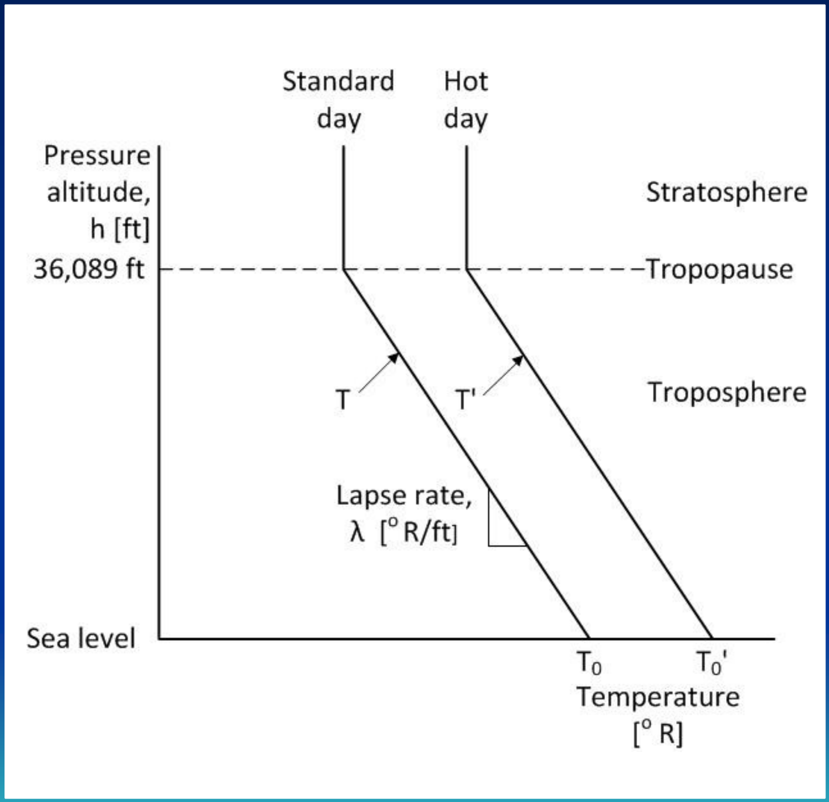
International Standard Atmosphere

- Definition of the atmosphere
- Definition of pressure altitude
- How an altimeter works
- Impact of hot or cold day on performance and geometric altitude measurement



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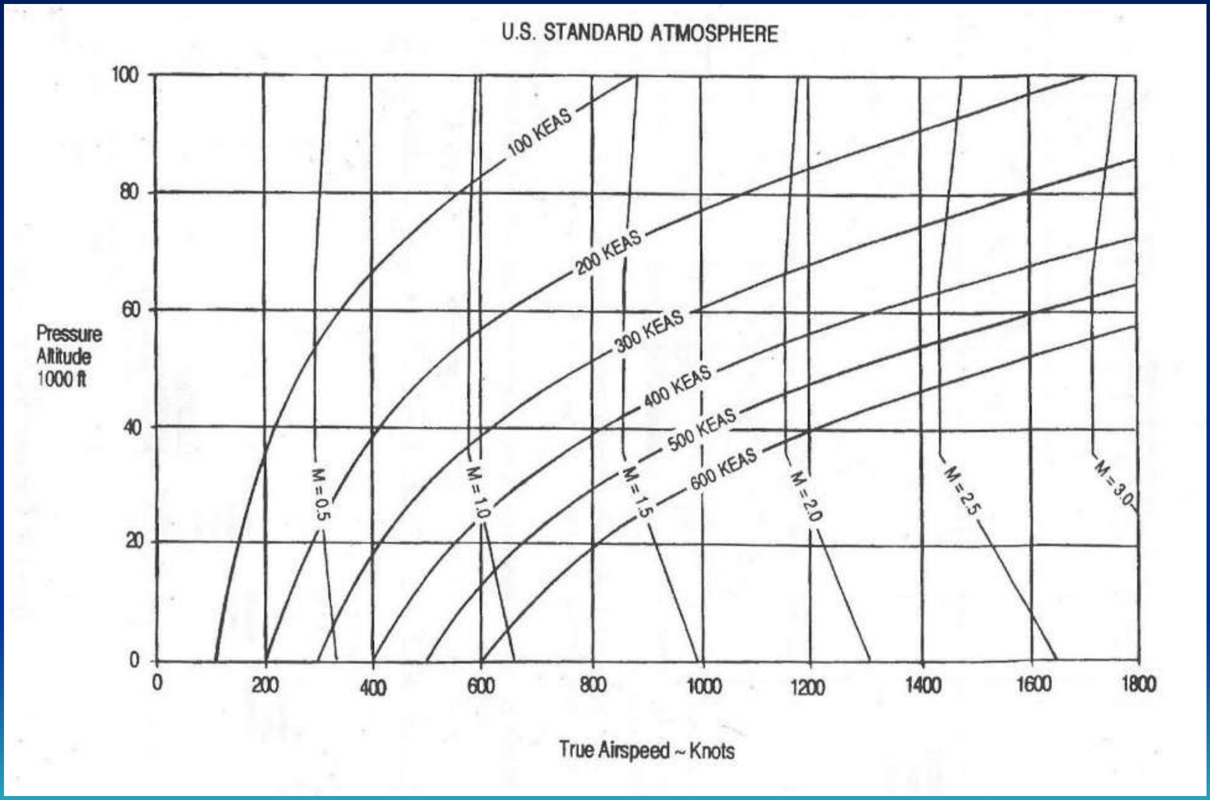
Relationship Between TAS, EAS, and Mach Number as Fn. Of Pressure Alt

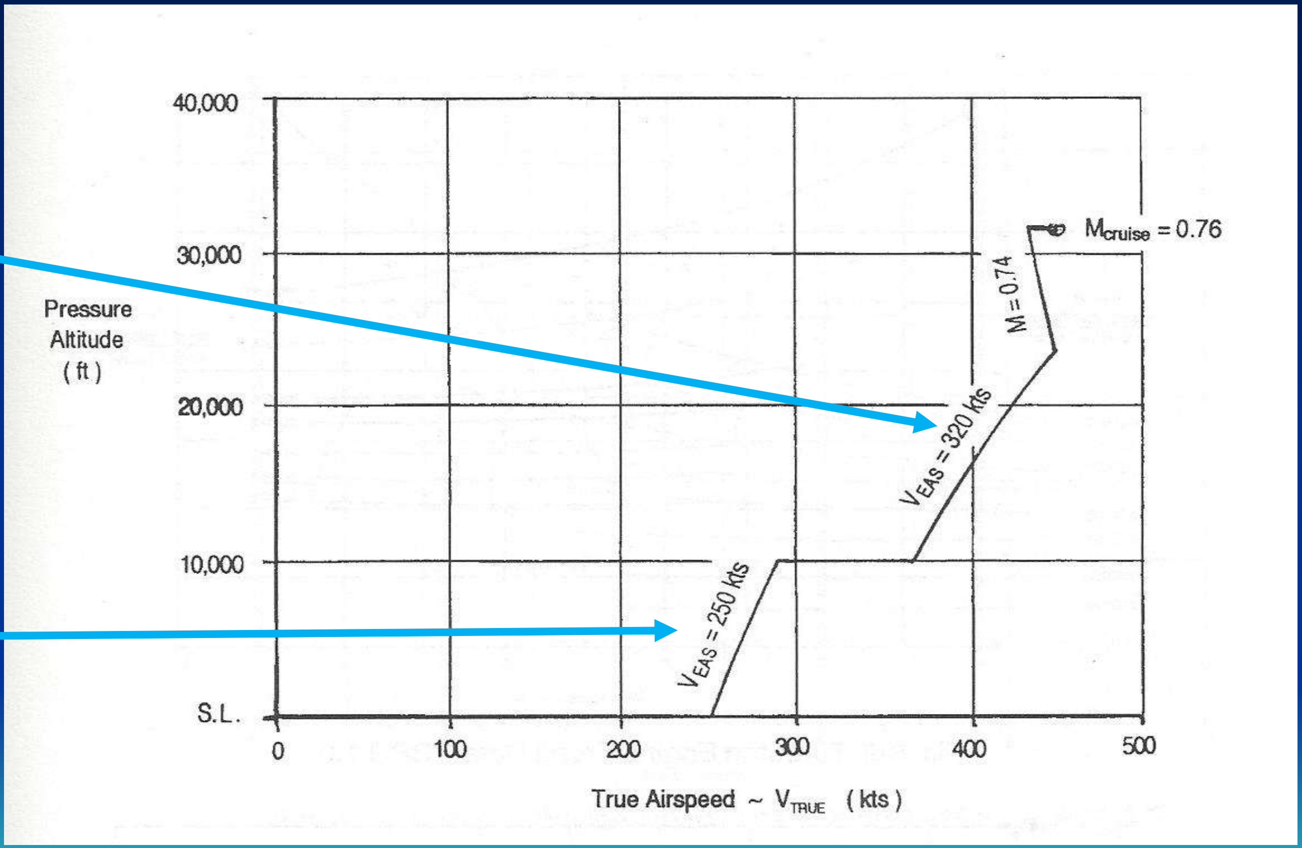


Source: Schaufele

DC-9 Climb Schedule

Airplane accelerating when flying at const. KEAS, must apply correction to climb thrust

FAR Part 91.117 :
If h_p < 10,000 ft.,
then $V_{IAS} \leq 250$ kt.



Source: Schaufele

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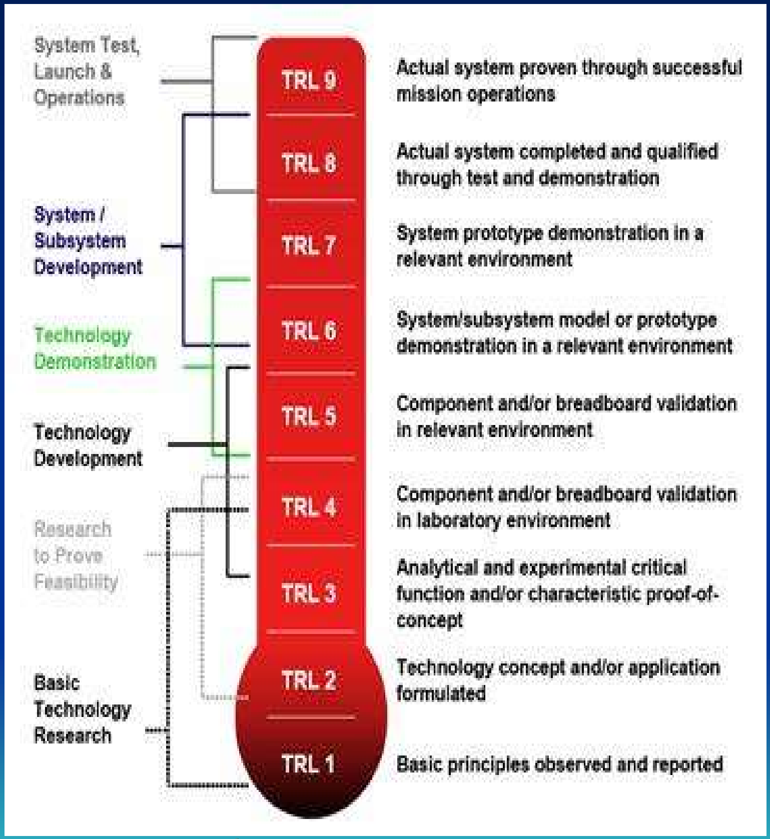
Defining Requirements

- Commercial aircraft: requirements defined by airlines working in concert with airframe, engine and systems manufacturers
- Military aircraft: requirements defined by the customer (usually the Federal Government) with contractor input
  - Interactions with contractors defined by law

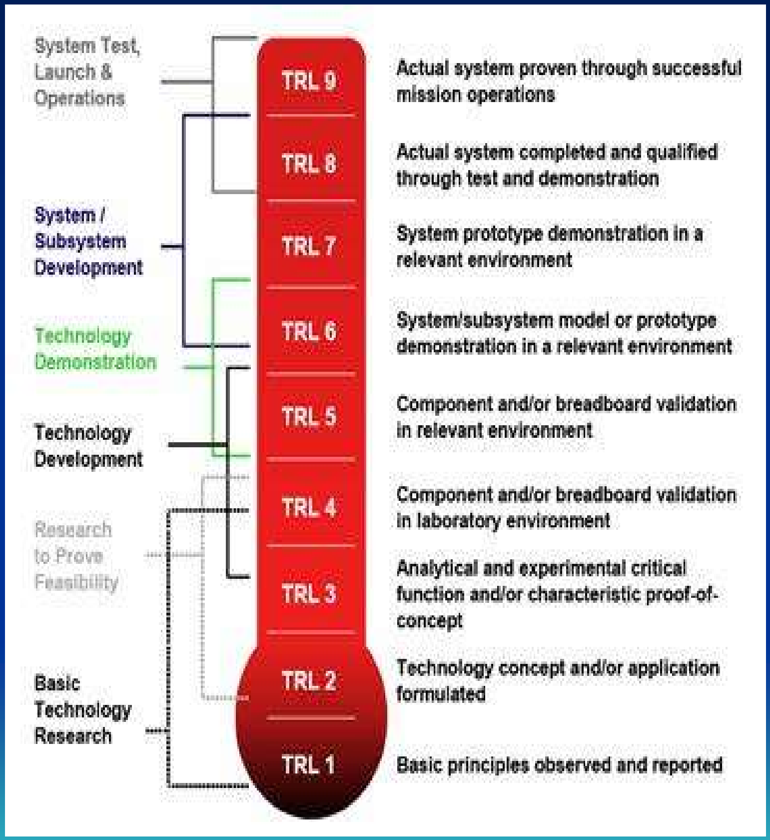
Risk Analysis

- Technical risk (Technology Readiness Level)
  - Not meeting specification and schedule (including those of team members)
- Economic risk
  - Depression
  - Fuel price
  - Exchange rates
  - Inflation
- Political risk



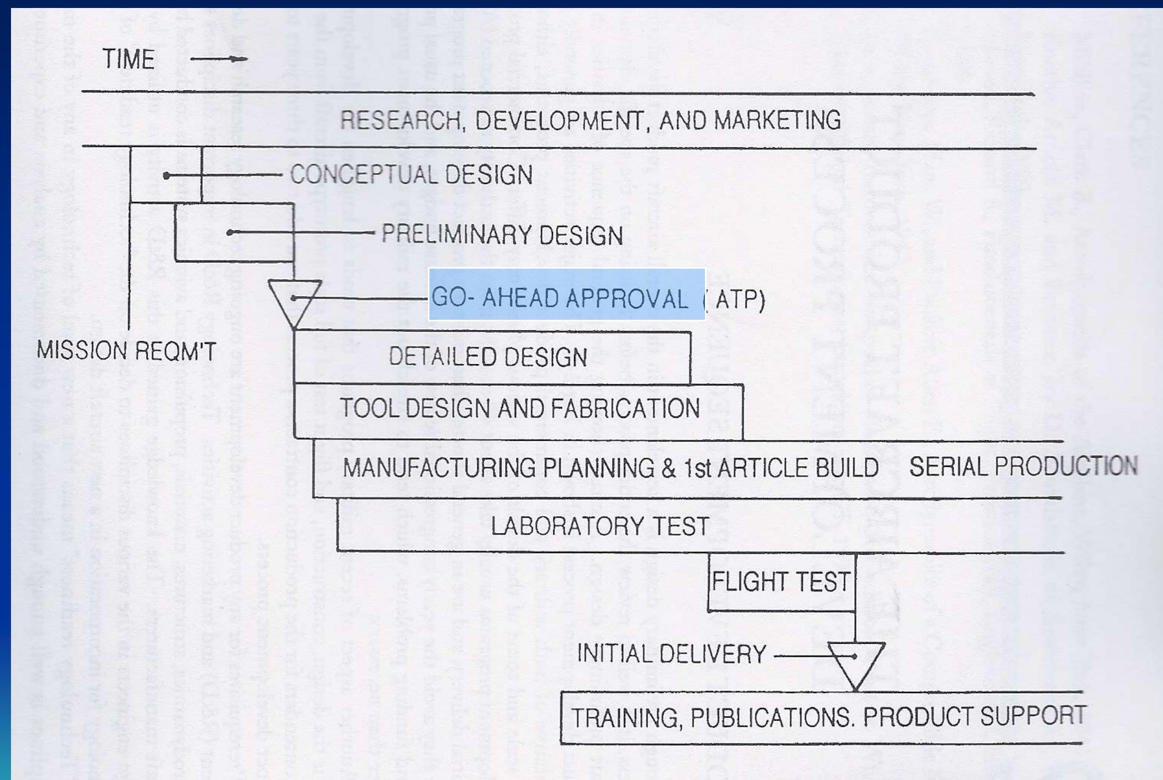
Technology Readiness Levels

- At project go-ahead, every system should be at TRL 7 or above



Commercial Development Schedule

- At project go-ahead (Authority To Proceed), every system should be at TRL 7 or above



Source: Schaufele

Risk Analysis

- Examples of failure
  - Hyfil blades for R-R RB211
  - Europrop TP400-D6 engines for A400M
  - Large scale composite manufacturing for B787.

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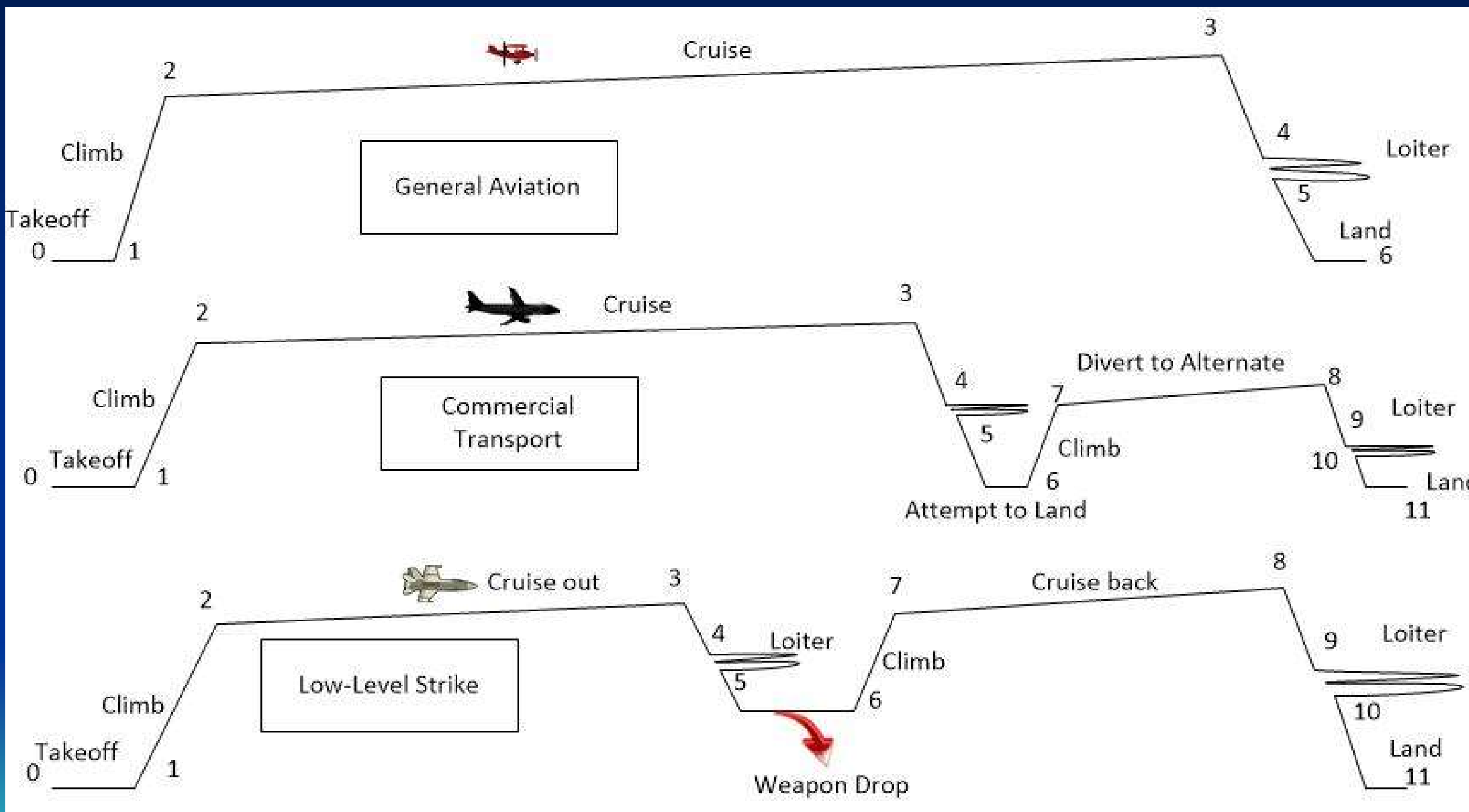
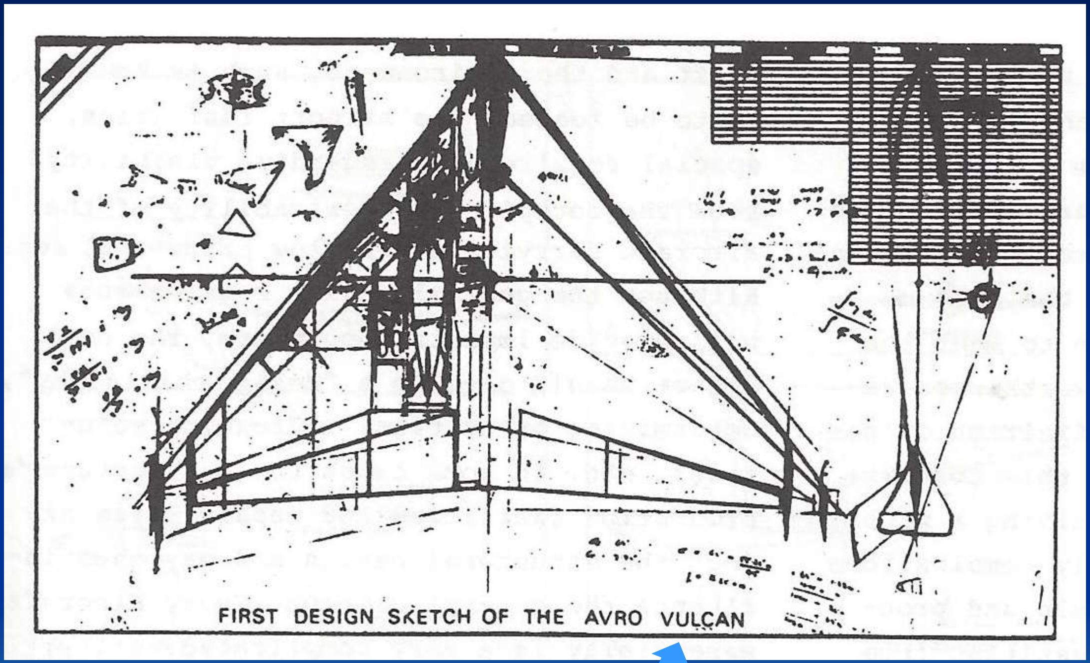
Sample Mission Profiles



Initial Sketch

- Initial trade studies
  - Planform shape
  - Cabin/Payload bay shape
  - Engine location
  - Etc.
- Select initial characteristics on competitive aircraft
  - T/W, W/S, TOGW

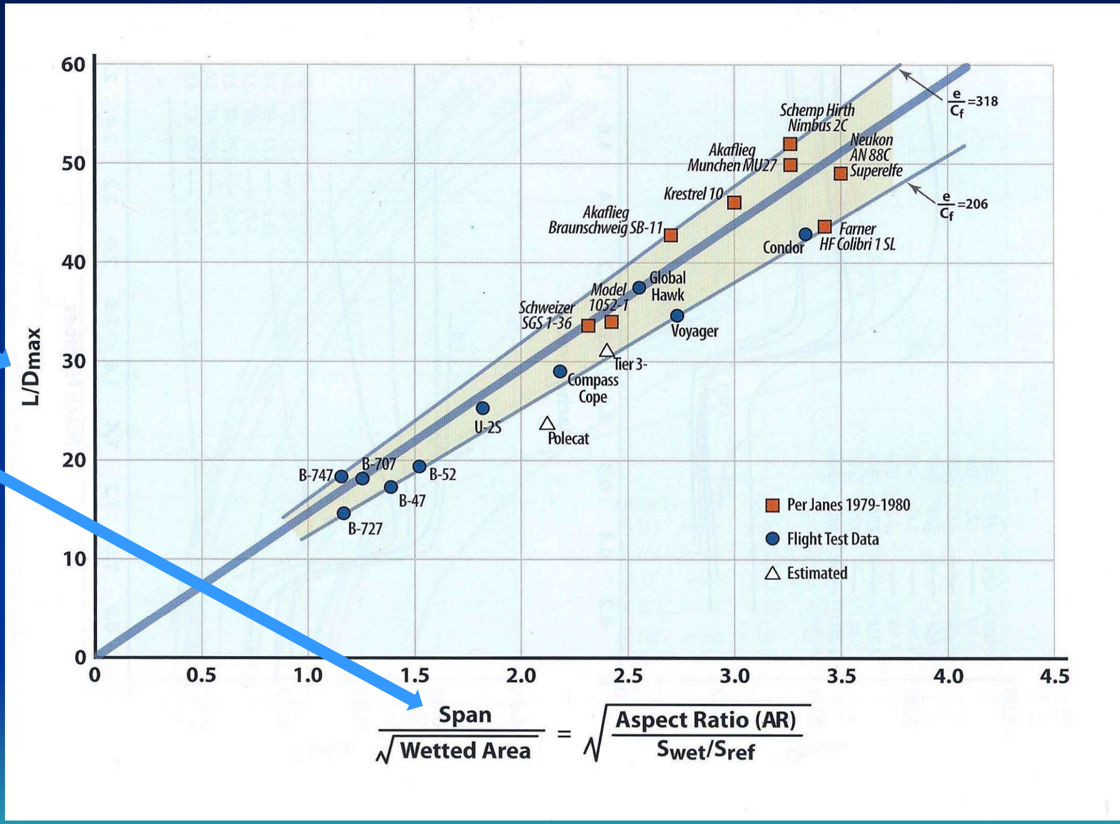


Source: www.vulcantothesky.org

Not much like final configuration

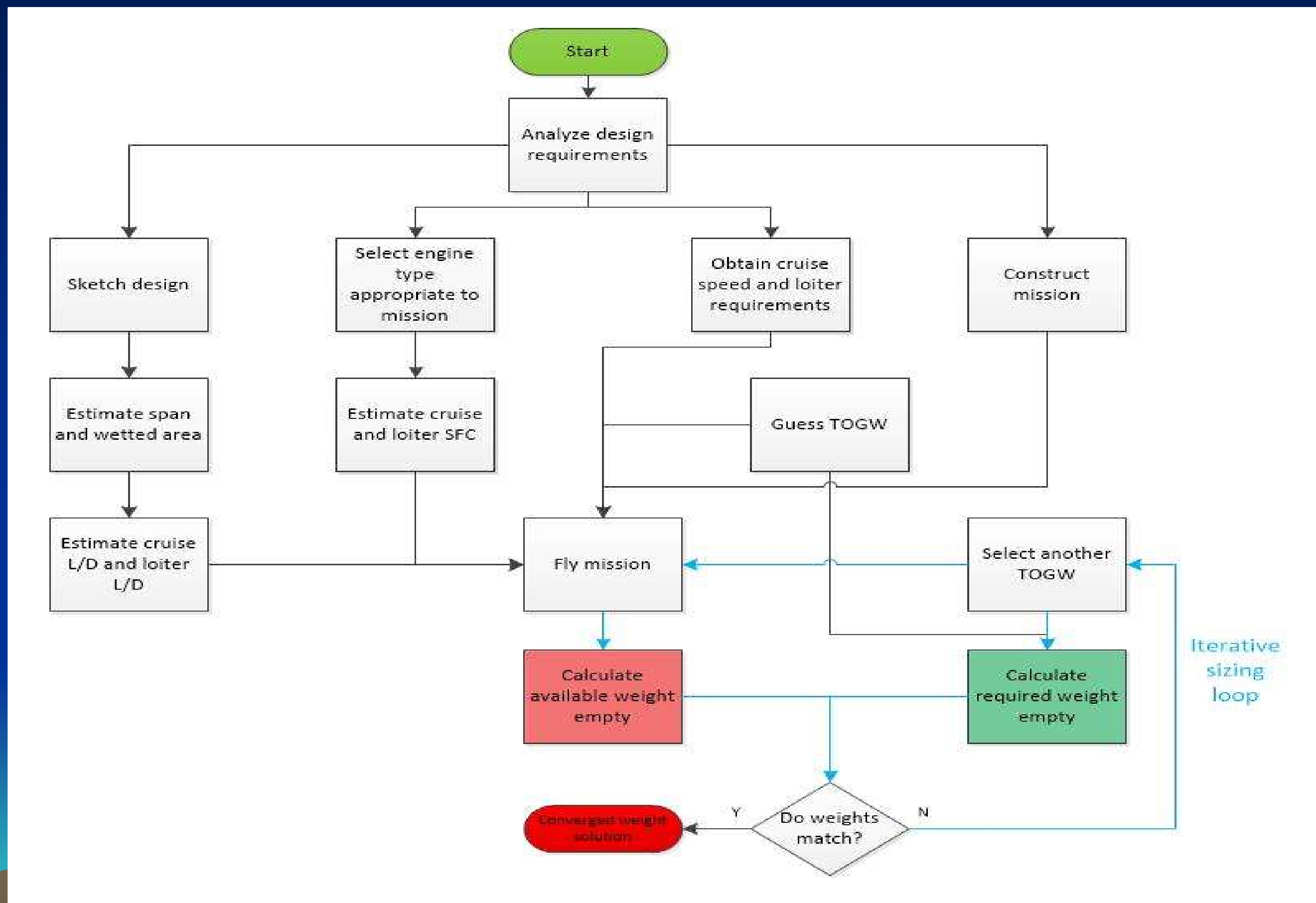
Initial Estimates of L/D, M, and sfc

- Estimate L/D from wing span and wetted area
- Estimate cruise Mach and sfc



Source: Nicolaai/Carichner.org

Initial Estimate of Take-Off Gross Weight



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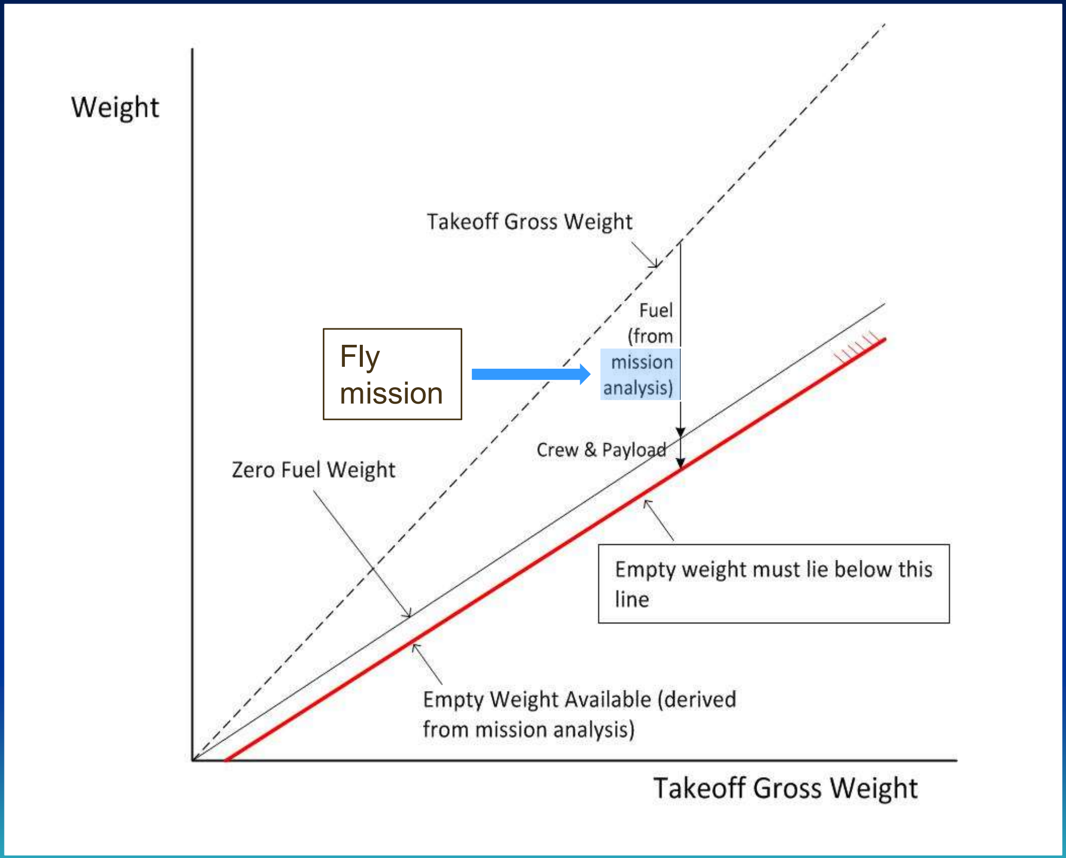
Empty Weight Available

- Empty weight available as a function of assumed TOGW



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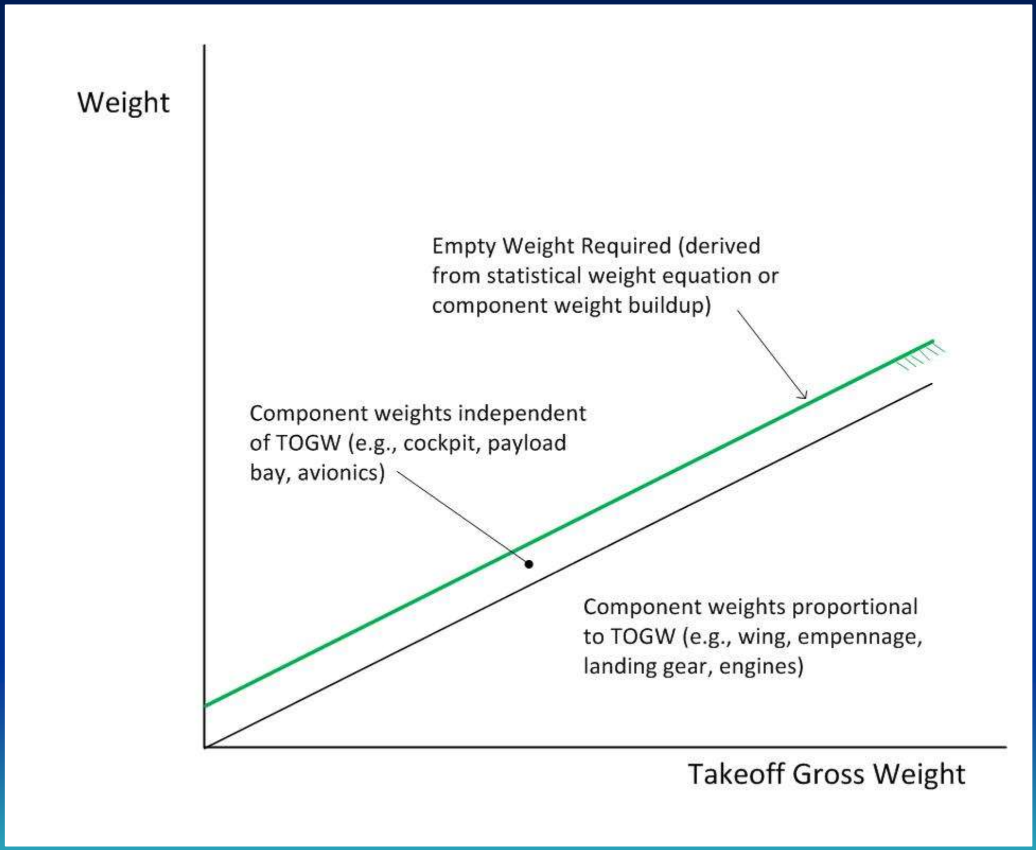
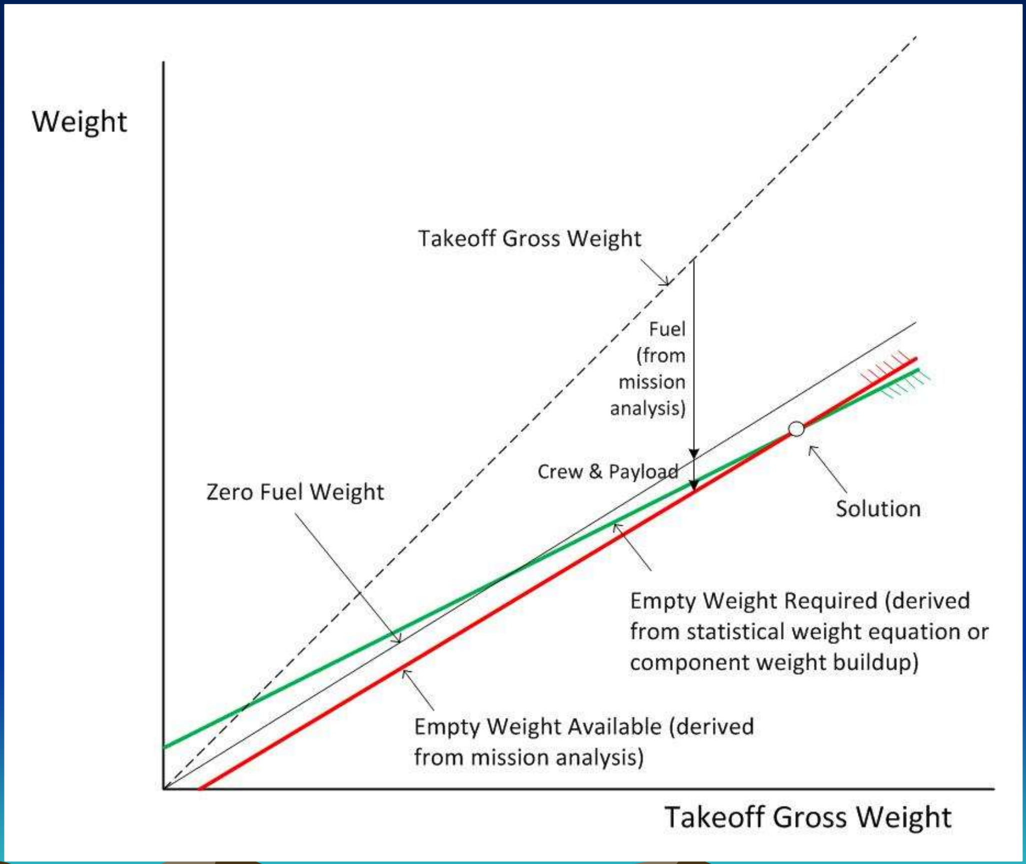
Empty Weight Required

- Empty weight <u>required</u> based on statistical weight relationship (or component weight buildup)



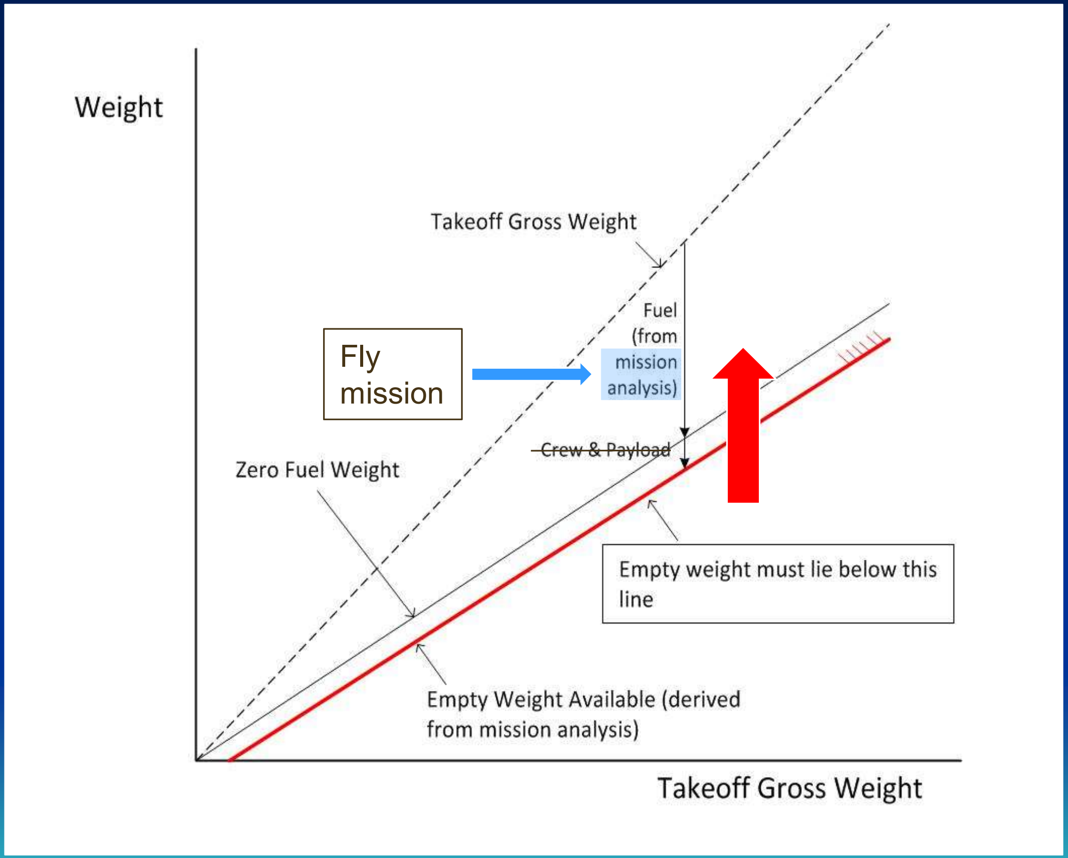
Empty Weight Solution

- Minimum empty weight is at intersection of empty weight available and required



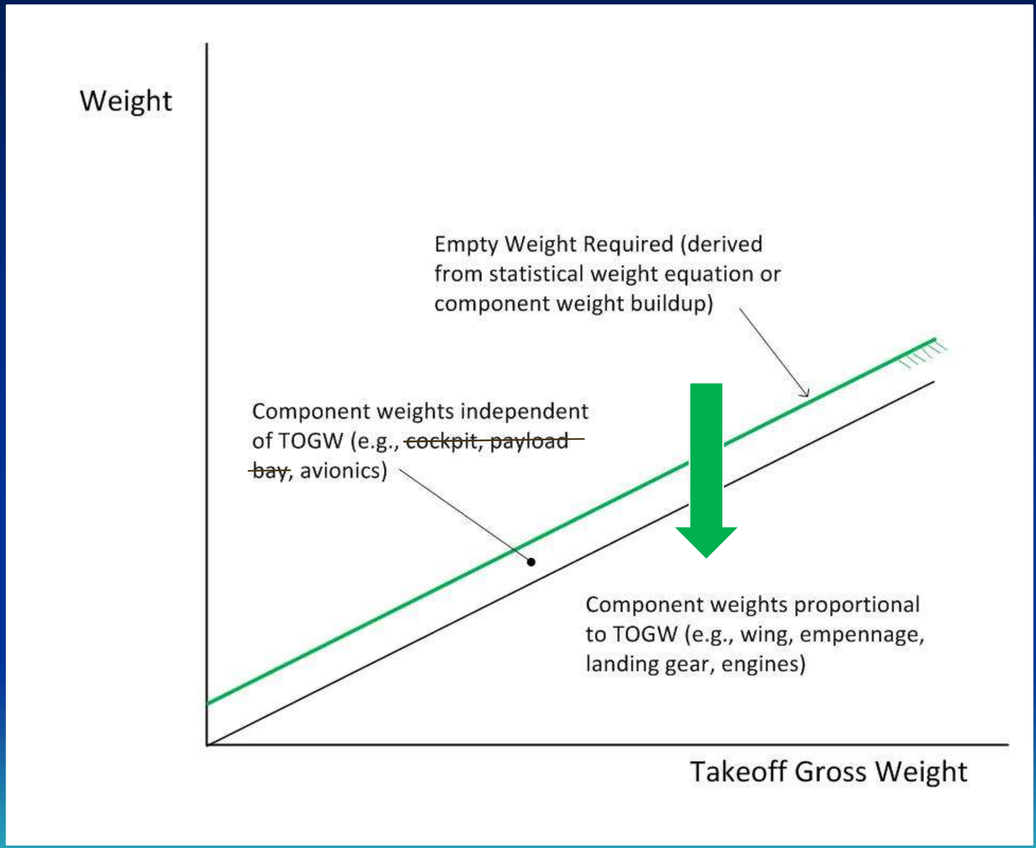
Empty Weight Available

- Minimum weight for unrefueled flight across Atlantic?
- Remove crew and payload
- Fixed weights include comm/nav systems



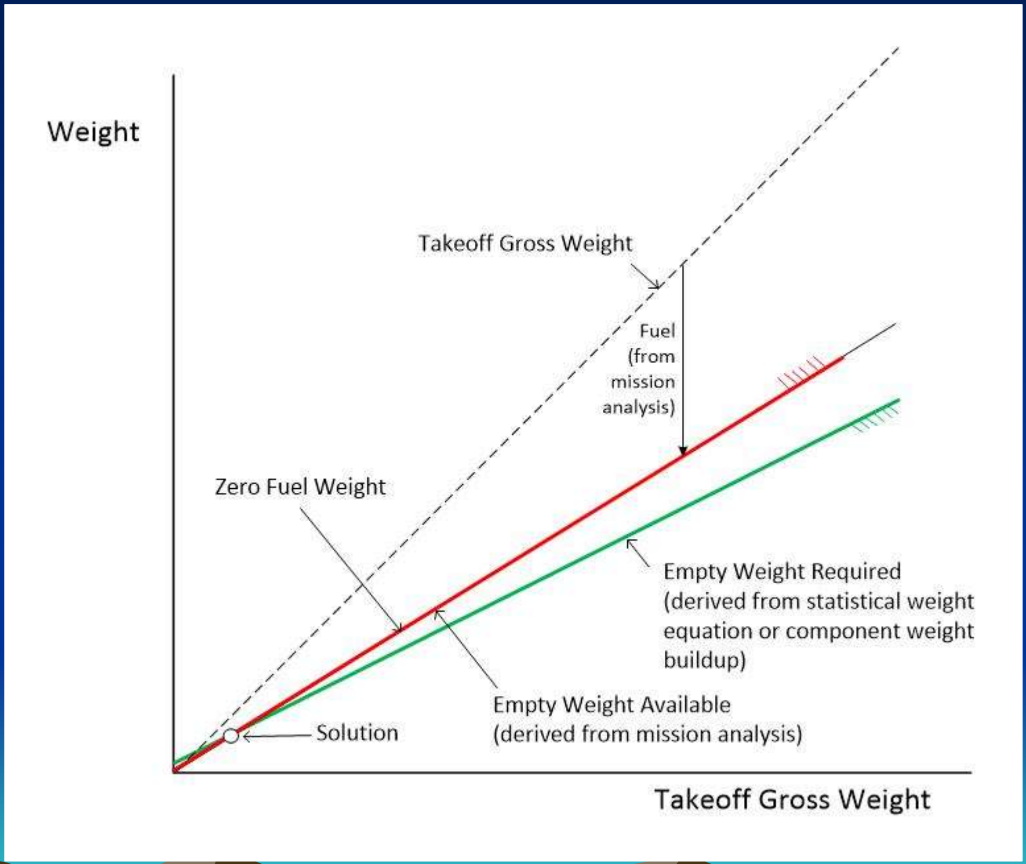
Empty Weight Required

- Remove cockpit and payload bay



Sensitivity to Payload and Crew Weight

- Elimination of crew and payload reduces TOGW significantly



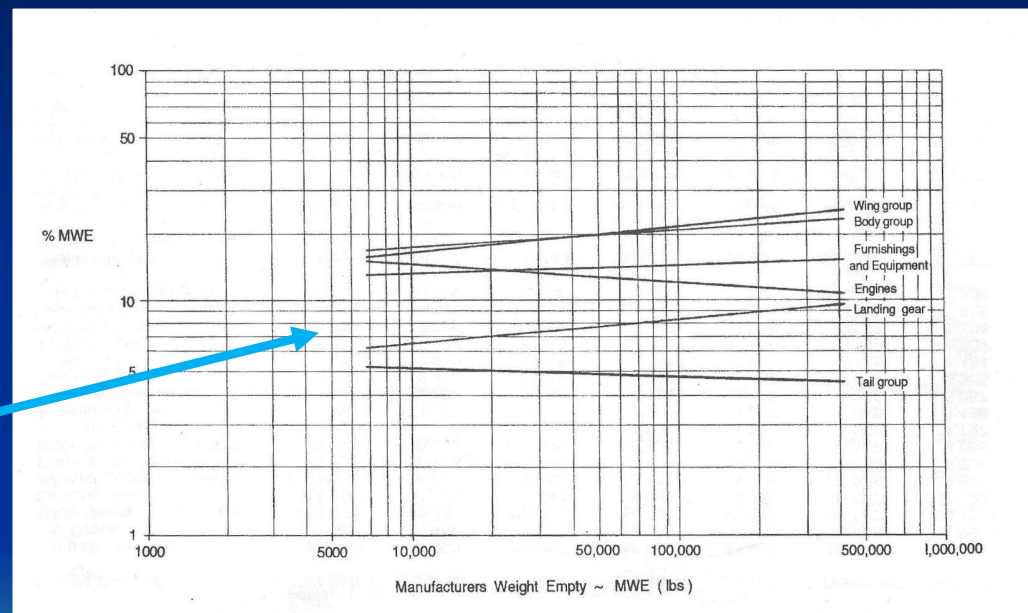
Model Airplane Flies Across Atlantic

- TAM-5
- August, 2003
- Flew from Canada to Ireland: 1,641 nmi (3038 km)
- TOGW = 11 lb (5 kg), dry weight = 6 lb (2.7 kg)
- Nav/comm system included GPS, autopilot, remote manual control

Source: www.barnardmicrosystems.com

Mission Sizing Program

- Excel spreadsheet for mission sizing
  - Solver for convergence of TOGW
  - Statistical weight equations for empty weight required
    - Adjust for group weight reduction factors
  - Modify spreadsheet for other points on payload-range plot



Source: Schaufele

Commercial aircraft group weight breakdown

Mission Sizing Program

- Excel spreadsheet for mission sizing
  - Solver for convergence of TOGW
  - Statistical weight equations for empty weight required
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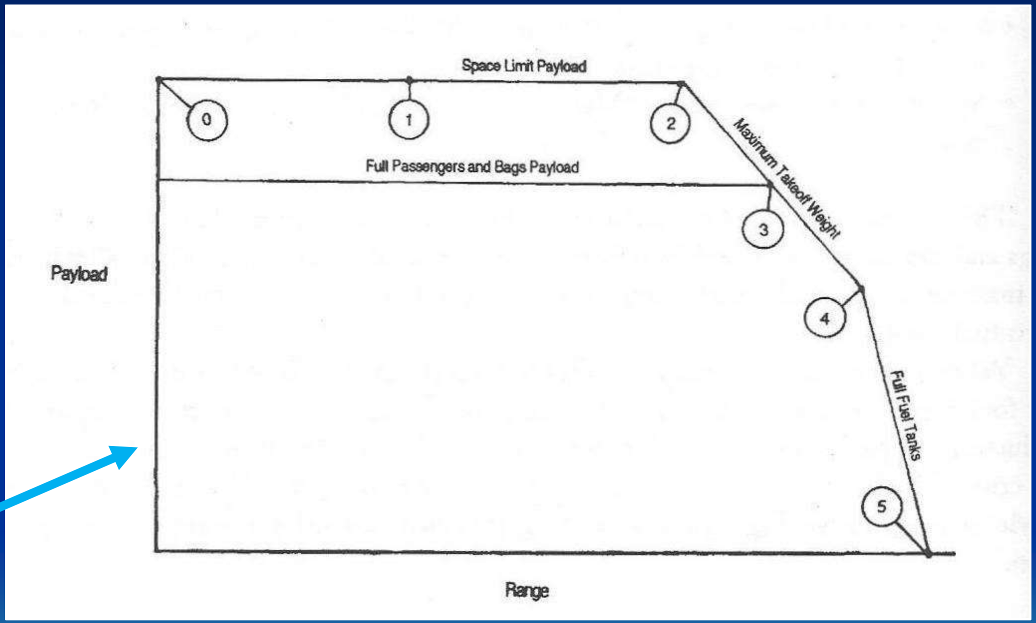
  - Modify spreadsheet for other points on payload-range plot



Source: Schaufele

Commercial aircraft payload-range plot

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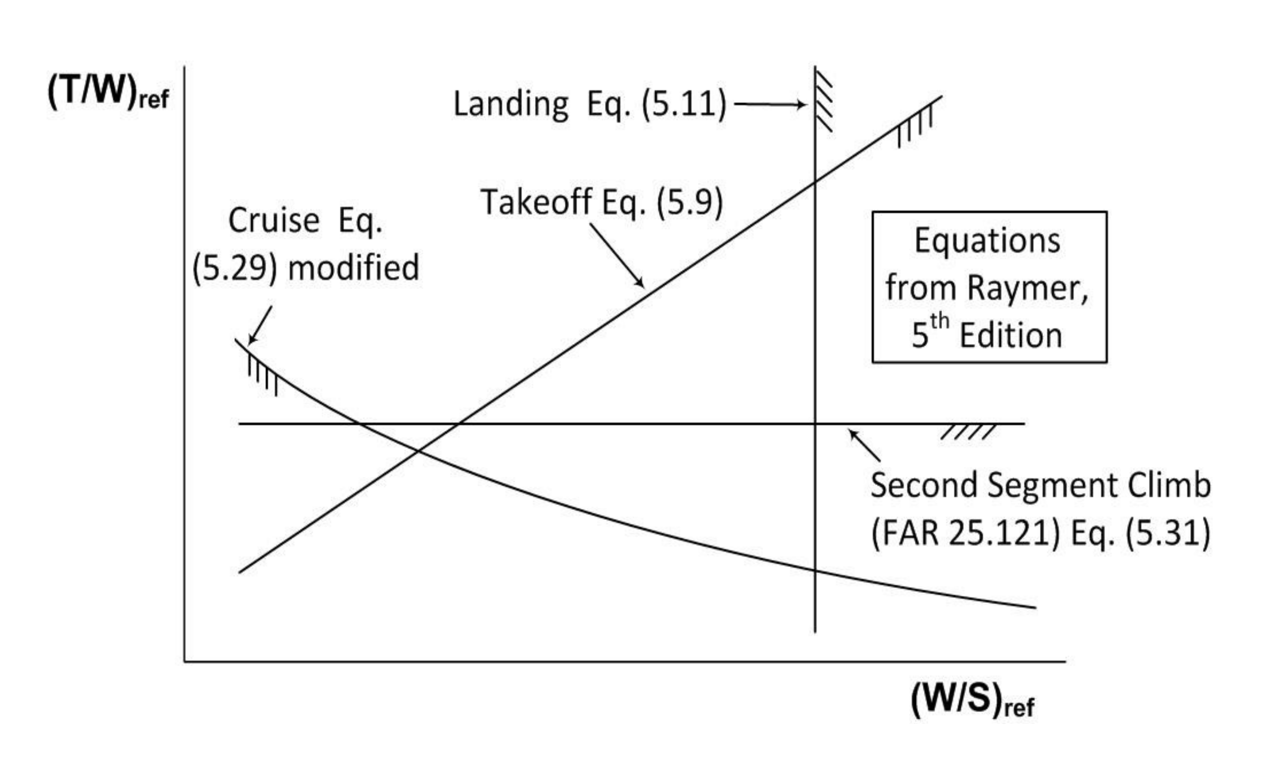
Commercial Thrust/Weight vs. Wing Loading

T_{ref} = Sea level static, standard day, all engines operating
W_{ref} = Maximum takeoff gross weight
S_{ref} = Reference wing area

Raymer:
Ch 5 T/W vs. W/S
Ch 17 Performance and Flight Mechanics
Ch 19 Trade Studies

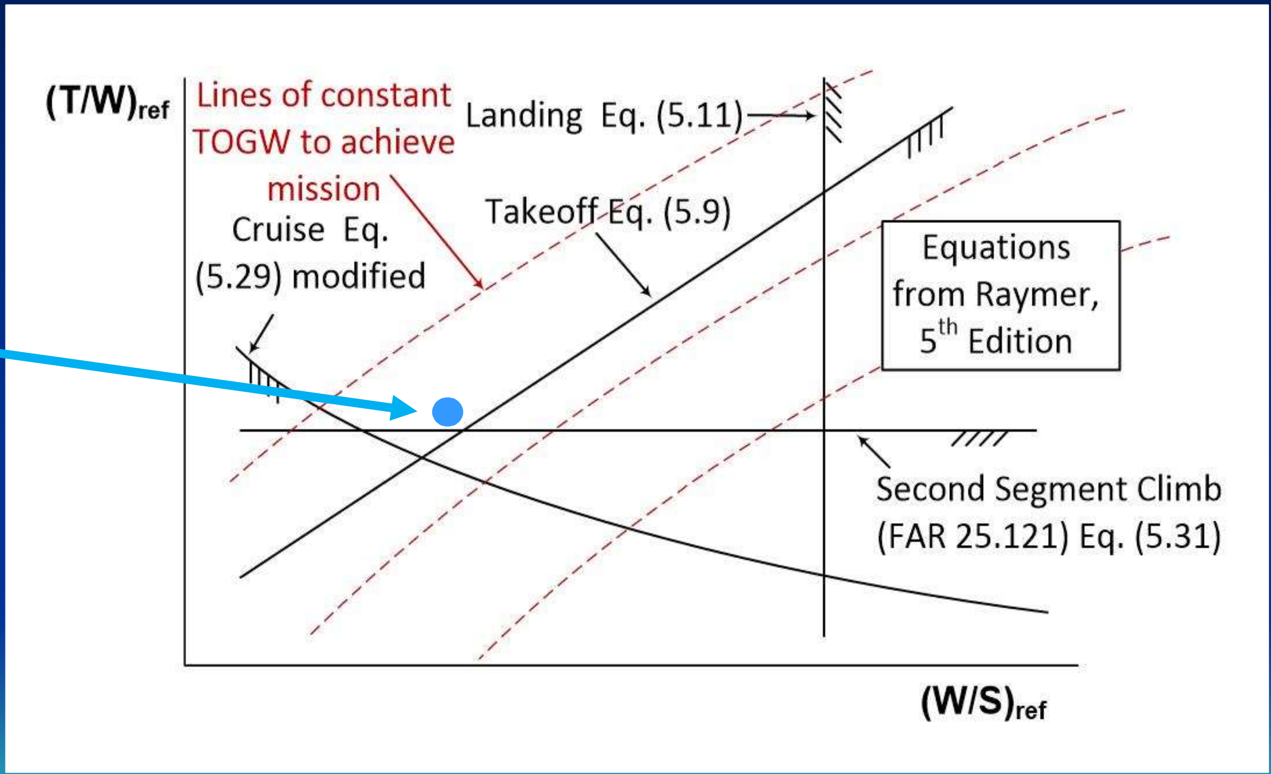


Commercial T/W vs. Wing Loading

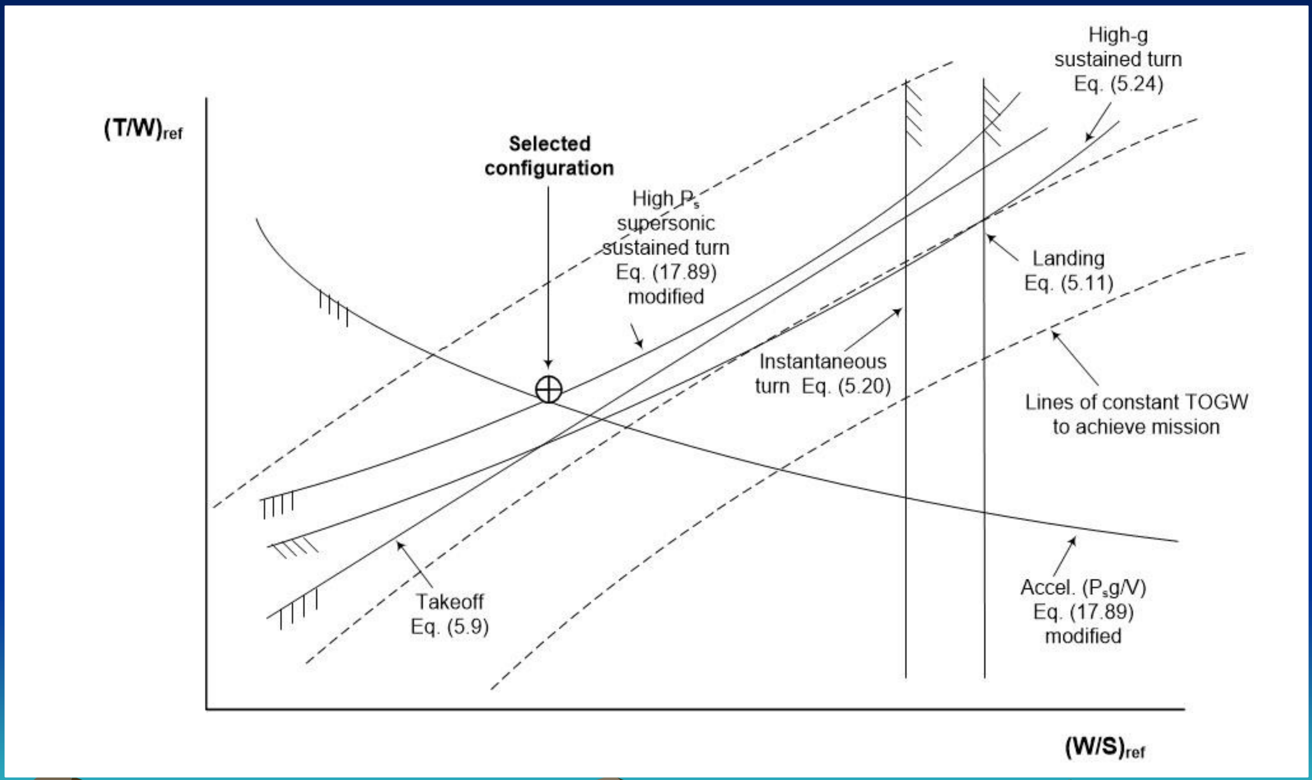
Select configuration with reserve of wing area

If higher MTOGW is offered:

- Aircraft not constrained by landing
- Extra volume available in wing fuel tanks for increased range

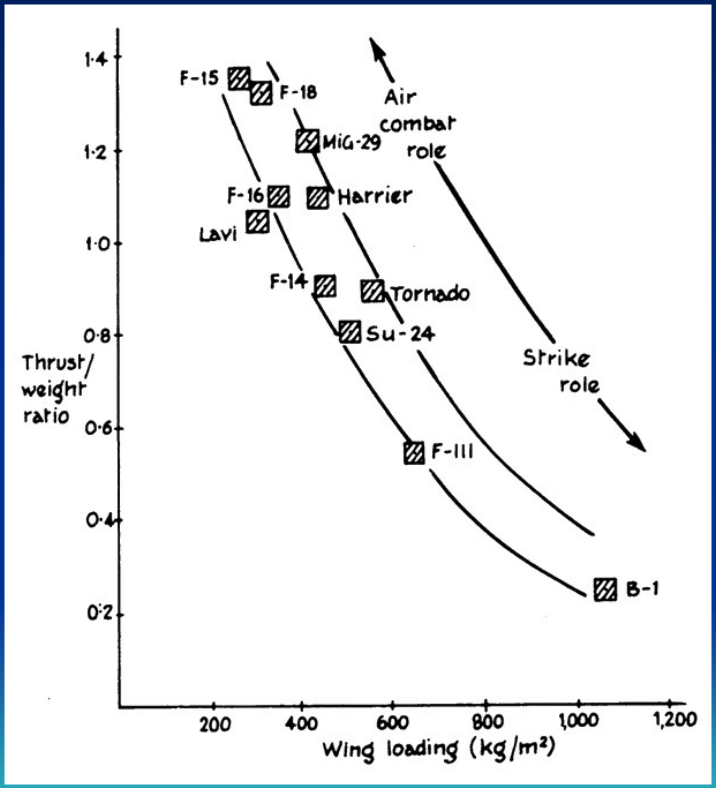


Military T/W vs. Wing Loading



Sizing and Performance – Military Aircraft

- Air superiority
  - High T/W, low W/S
- Bomber/strike/interceptor
  - Low T/W, high W/S



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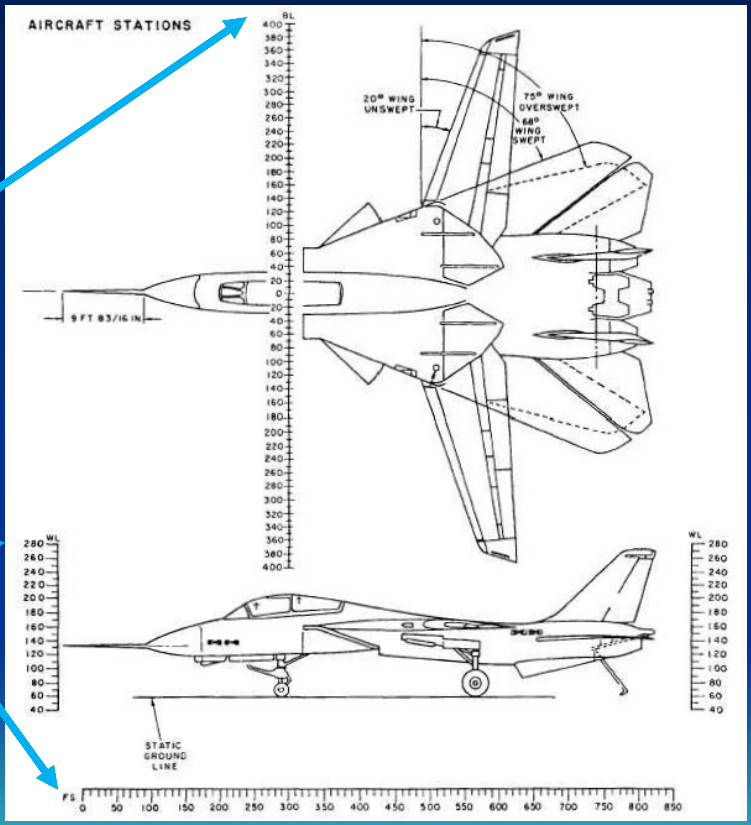
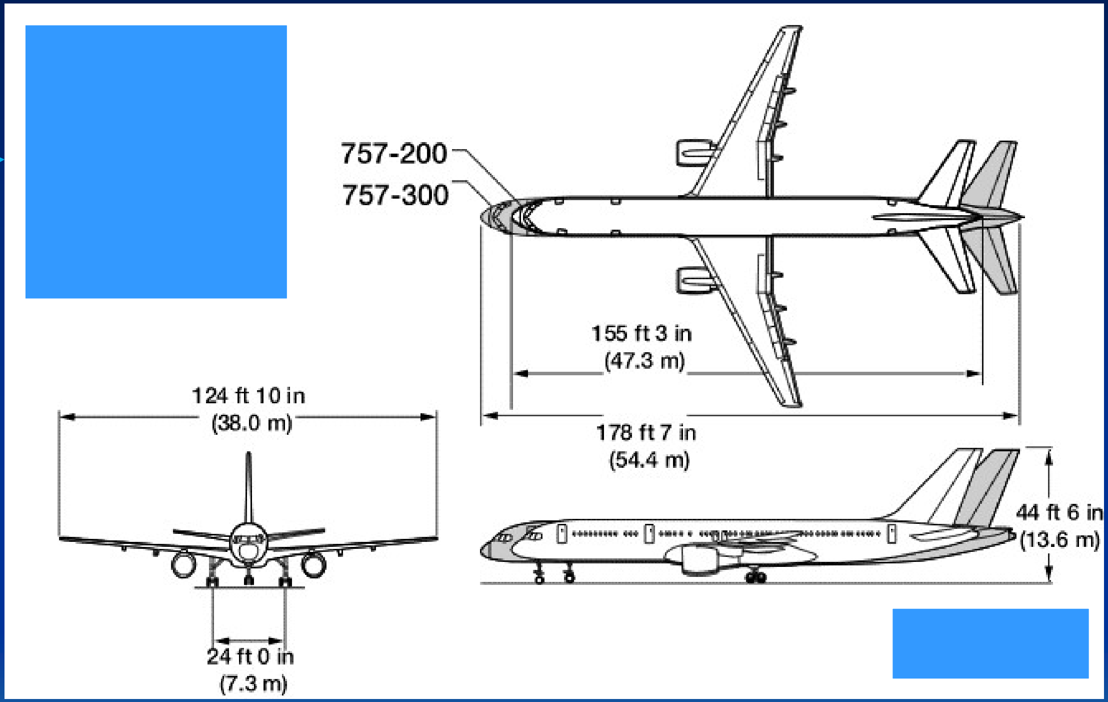
Drawing Axes and Cutting Planes

- X-axis (+ve aft):
  - Cutting plane is Fuselage Station (FS)
- Y-axis (+ve to starboard):
  - Cutting plane is Butt line (BL)
- Z-axis (+ve up):
  - Cutting plane is Waterline (WL)



Third-Angle Projection Three View

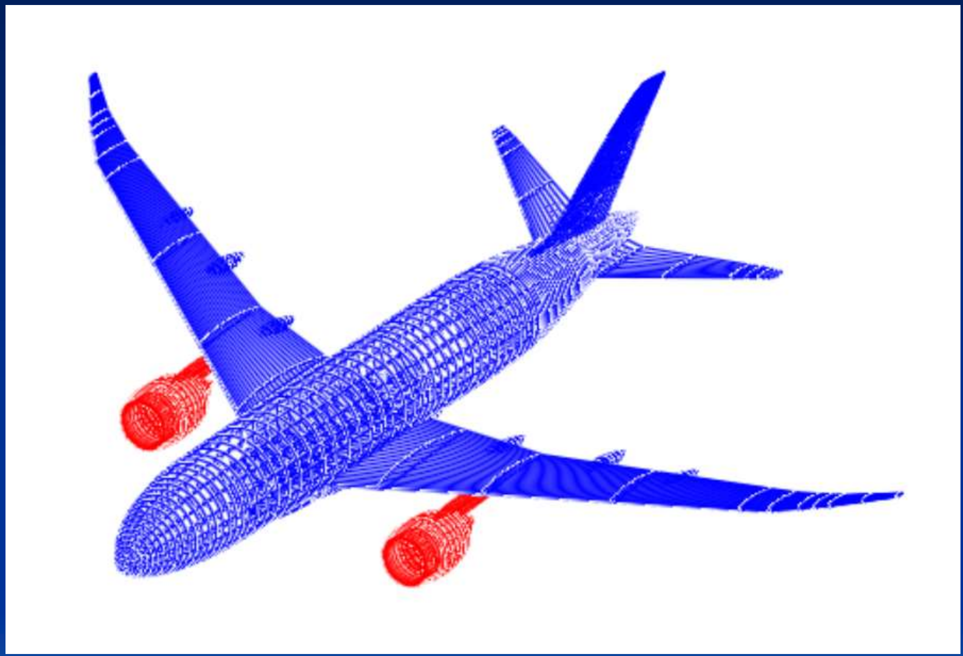
Put Characteristics Block here



Put Title Block here

Outer Mold Line (OML)

- OML is definition of the outer surface of aircraft
- Use Vehicle Scratch Pad (www.openvsp.org)
  - NASA open source parametric geometry
  - Large 'hangar' of existing and conceptual designs
  - Links to other analysis software, such as VSPAERO (vortex lattice solver)



Characteristics Block

Goes in top LHS of three-view

Characteristic	Wing	Horiz. Tail	Vert. Tail
Area (sq ft)			
Aspect Ratio			
Span (ft)			
Root Chord (ft)			
Tip Chord (ft)			
Taper Ratio			
M.A.C. (ft)			
Λ @ ¼ chord (^{0})			
t/c root			
t/c tip			
Dihedral (^{0})			

Design Takeoff Gross Weight (lb):

Engine Type:

Installed Takeoff Thrust SLS Std Day (lb):

Drawing Title Block

Goes in bottom RHS of drawing

Drawing Title	
Configuration Number	*Drawing Number*
Drawn By:	Approved:
Scale:	Revision No:
Date:	Revision Date:
Company Name	

Source: Schaufele

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Propulsion System Choices

- What kind of engine to select


- Where to install it


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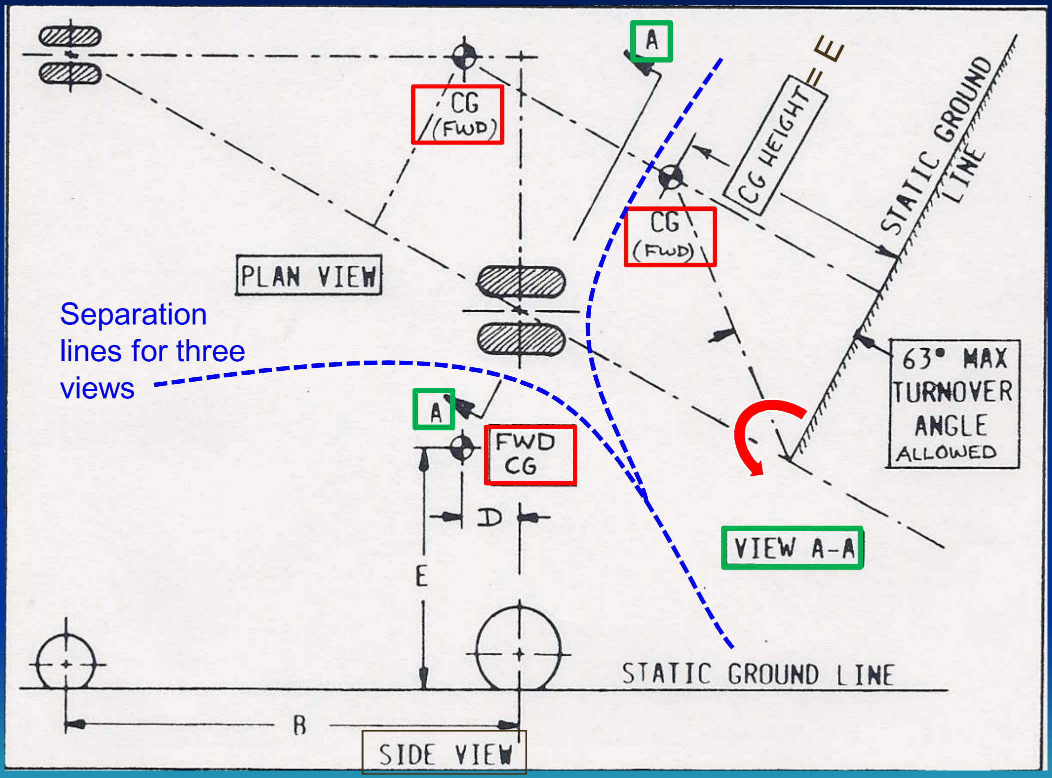
Lateral Tip-over Margin

- You don’t want this to happen
- Engine run mishap at Eielson AFB (Feb 2003)
- Note axis of rotation (line between contact point on ground of NLG and starboard MLG)

Source: www.ar15.com

Lateral Tip-over Margin

- Make scrap view in plane normal to line between ground location of NLG and MLG
- Assume c.g. height of commercial aircraft is at floor level
- Max elevation of <u>forward</u> c.g. from tip-over axis
  - 54^0 if carrier-based
  - 63^0 for all others

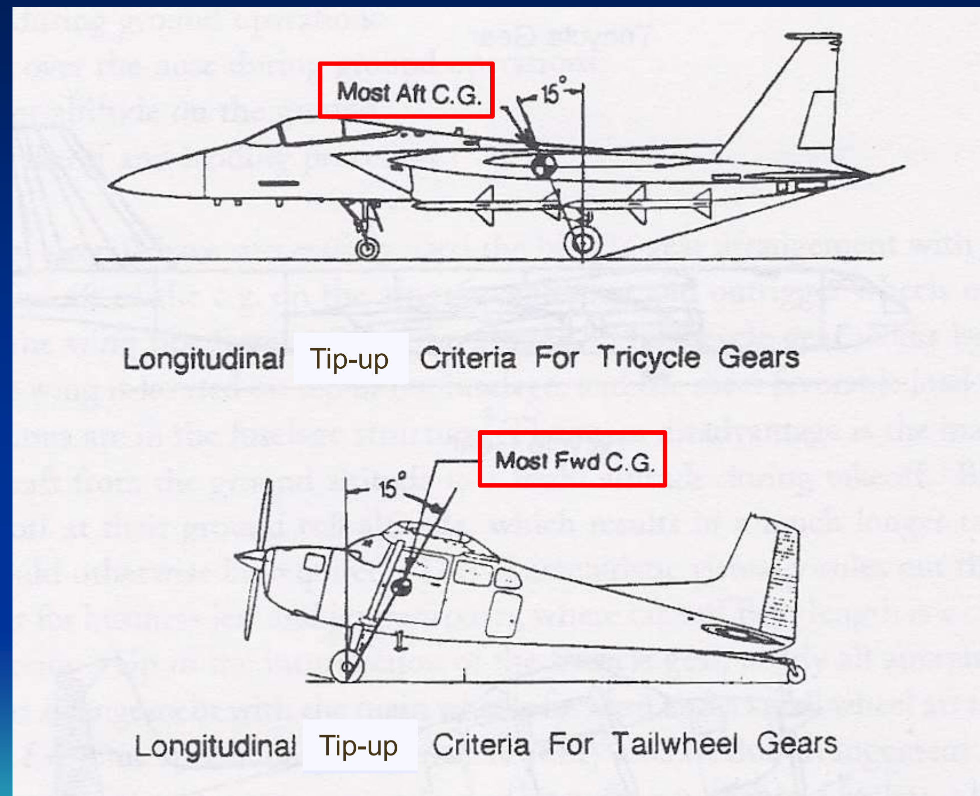


Source: Roskam

Longitudinal Tip-up Margin

- For commercial aircraft, for first estimate assume C.G. travel is 15 – 35% MAC
- Margin for tricycle layout is approximate
  - Less for unswept wing
  - More for delta wing
- For taildragger
  - More for soft field ops

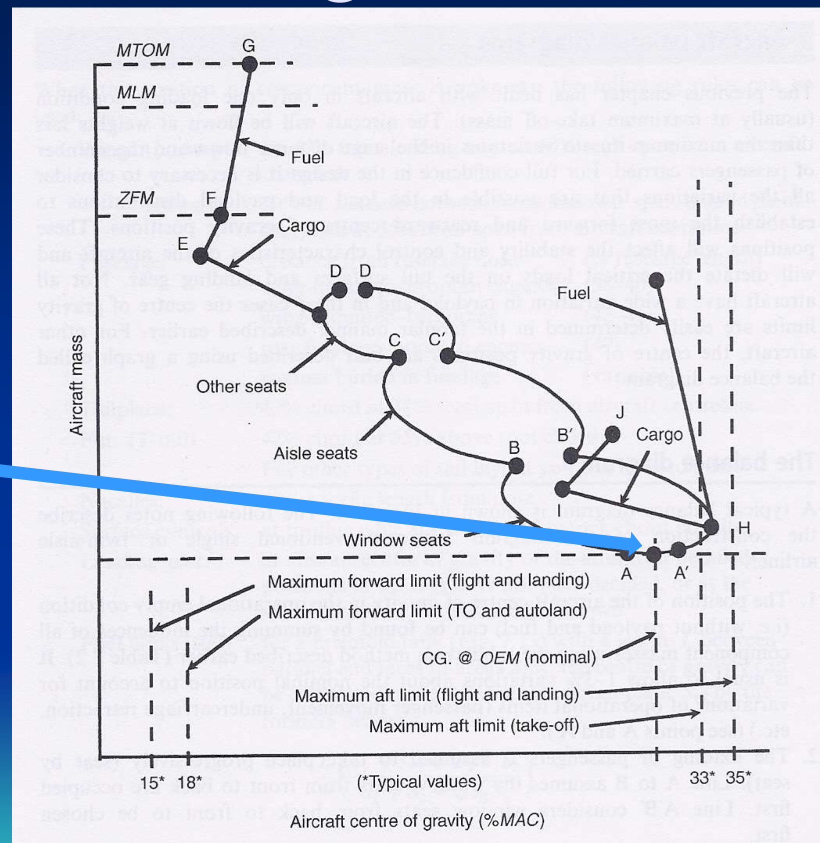
Note: MLG is usually not on same buttline plane as MAC



Source:Schaufele

Potato Plot for Fuselage-Mounted Twin

- As passengers and cargo are loaded, c.g. moves progressively forward
- At empty weight, c.g. is close to aft limit



Source: Jenkinson, Simpkin, Rhodes

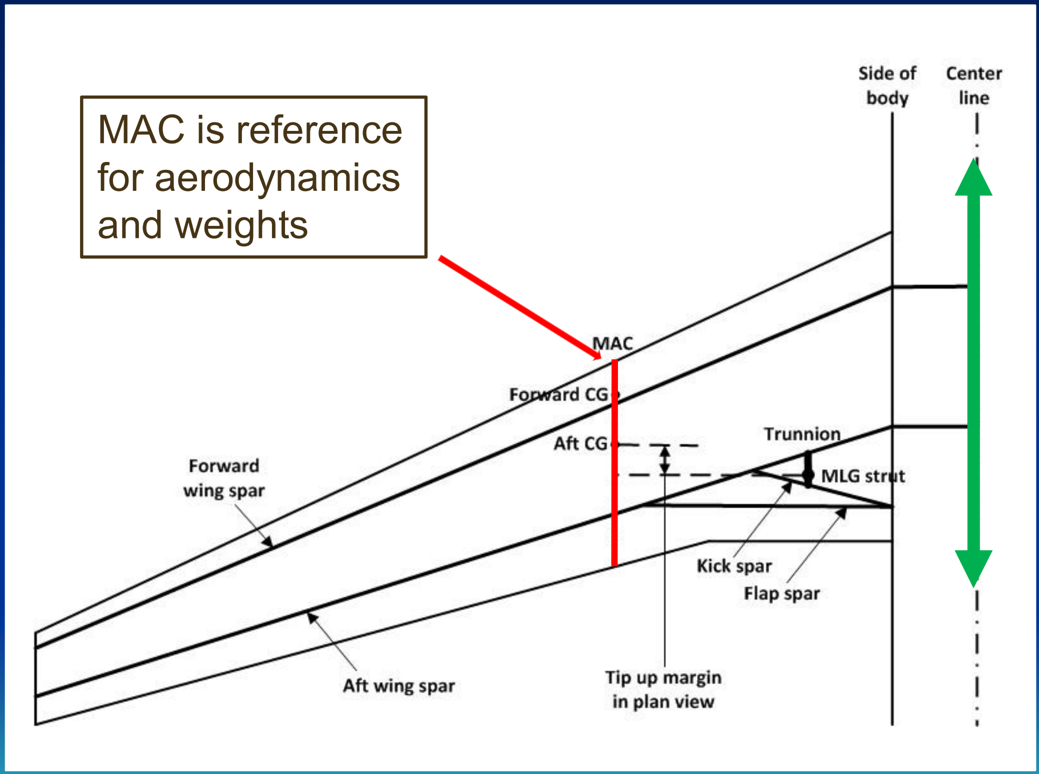
Effect of snow on pylon and horizontal stabilizer

Source: Jeffrey Cliffe

Buffalo NY 2006

Effect of Λ or AR on MLG Design

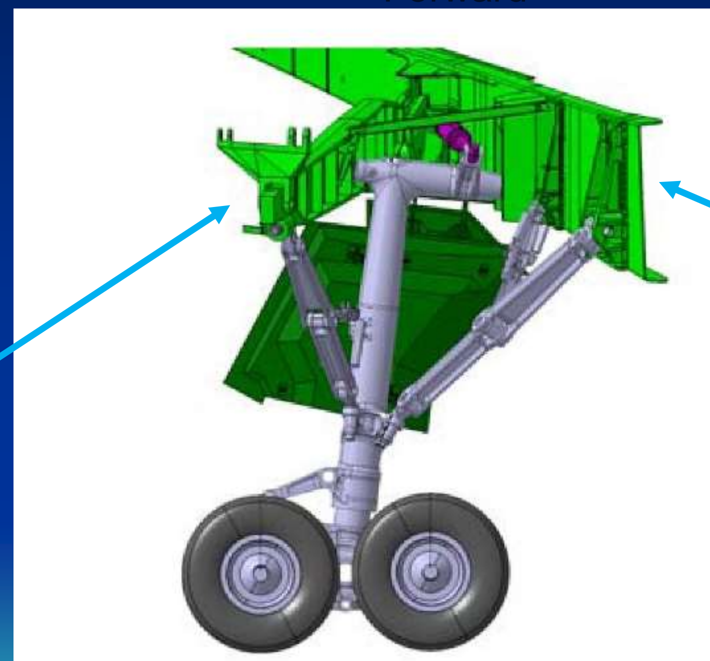
- Typical CG limits:
  - Fwd: 15% MAC
  - Aft: 35% MAC
- As Λ or AR increase, aft CG limit moves further aft relative to MLG
- As Λ increases, $\alpha_{liftoff}$ also increases, forcing MLG further aft



Move fuselage to put CG in correct location

787 MLG Cant

- Can permit approx. 15^0 cant in MLG oleo strut



B787 MLG

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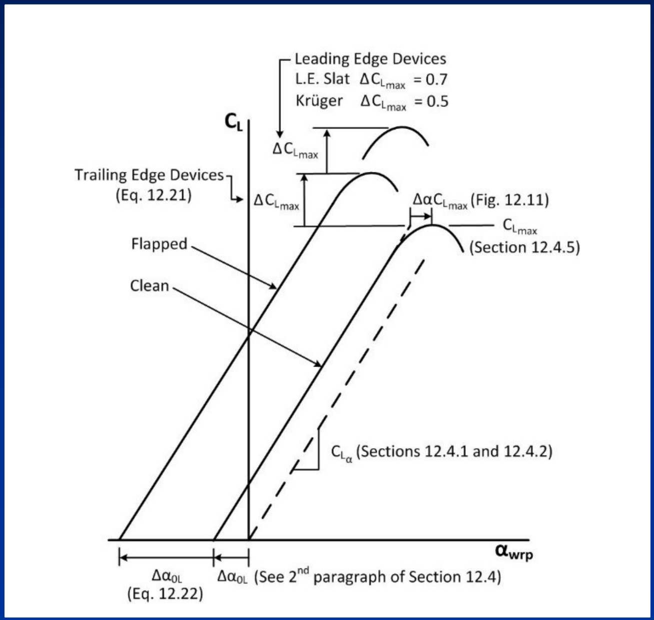
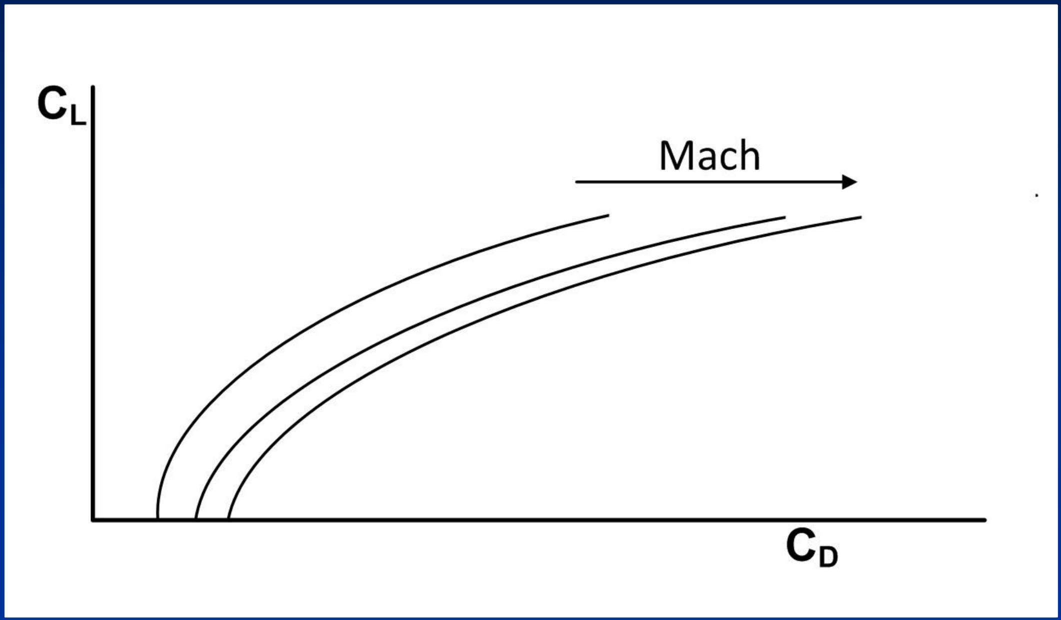
C_L vs. Alpha and Drag Polars



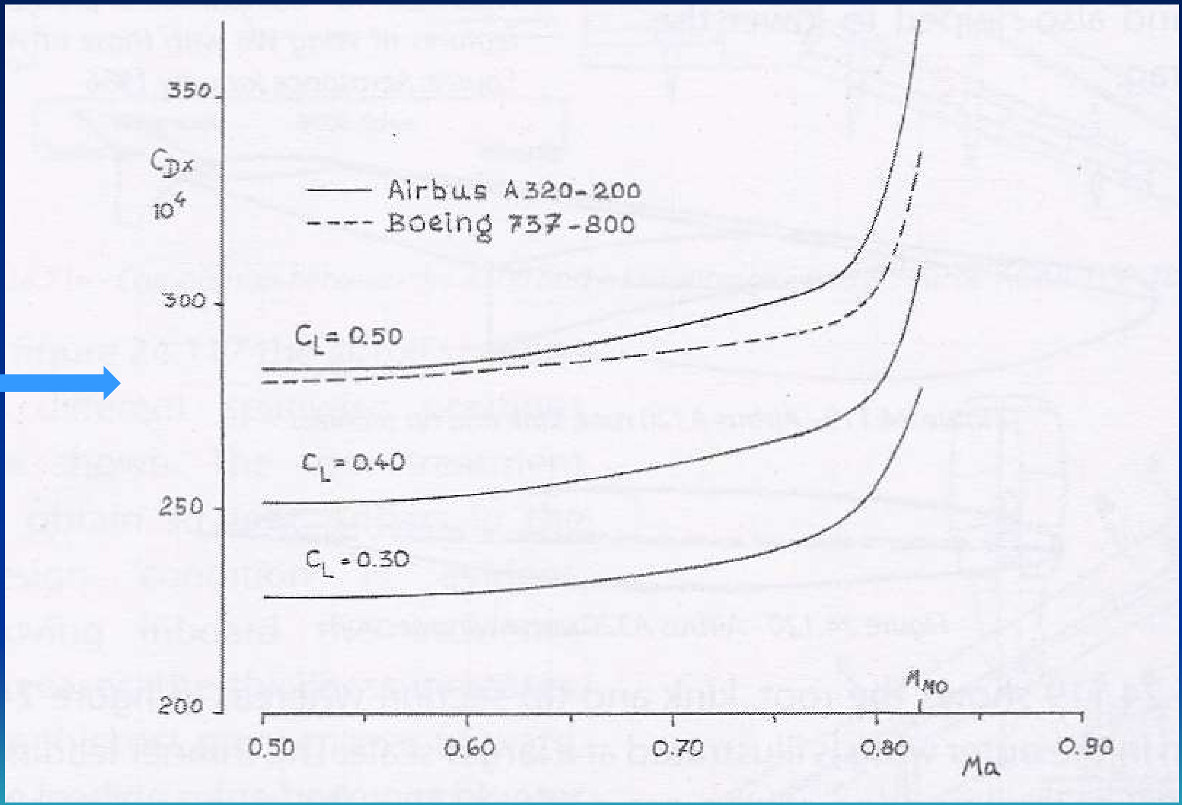
C_L vs. alpha



Drag polars

Comparative Drag Plots

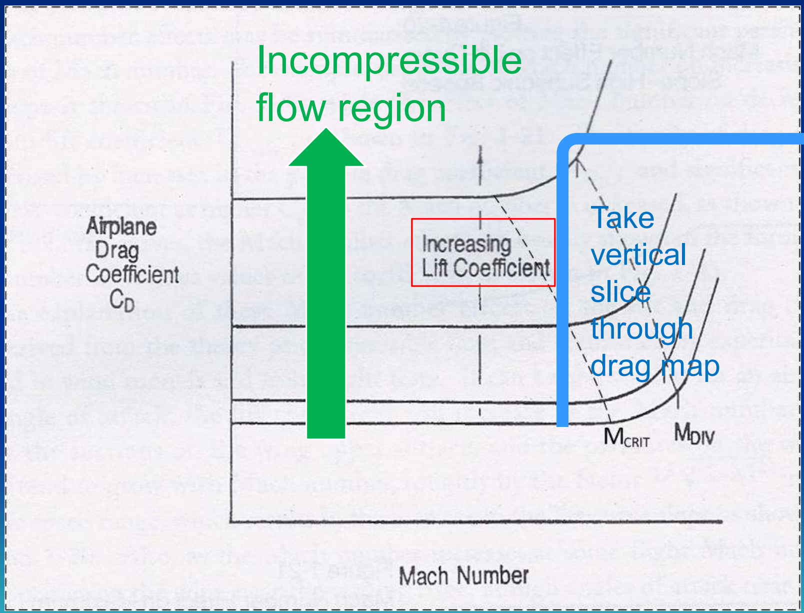
- Obert "Aerodynamic Design of Transport Aircraft" 2009
  - Many examples of commercial aircraft drag plots
- Schaufele "The Elements of Aircraft Preliminary Design"
- Shevell "Fundamentals of Flight" 1989
  - DC-10 L/D and ML/D

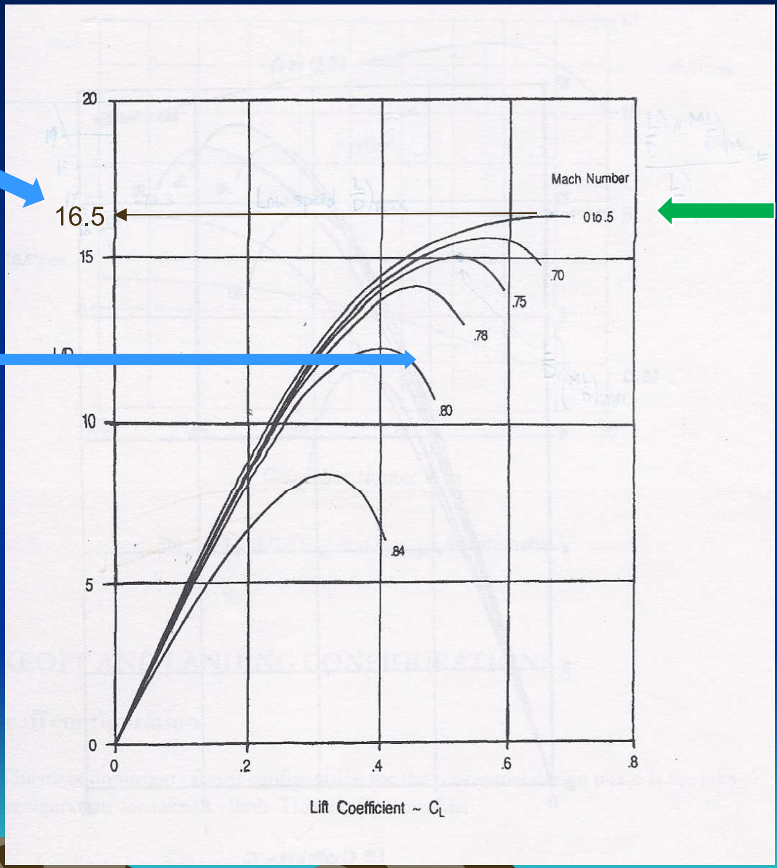


Source: Obert

DC-9 Lift/Drag Ratio vs C_L

- Max low speed L/D =16.5



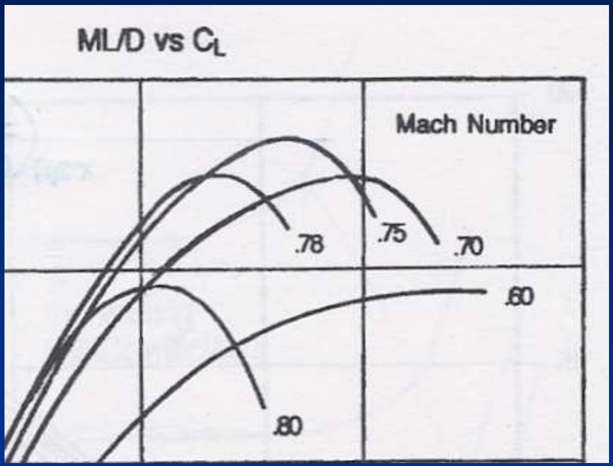


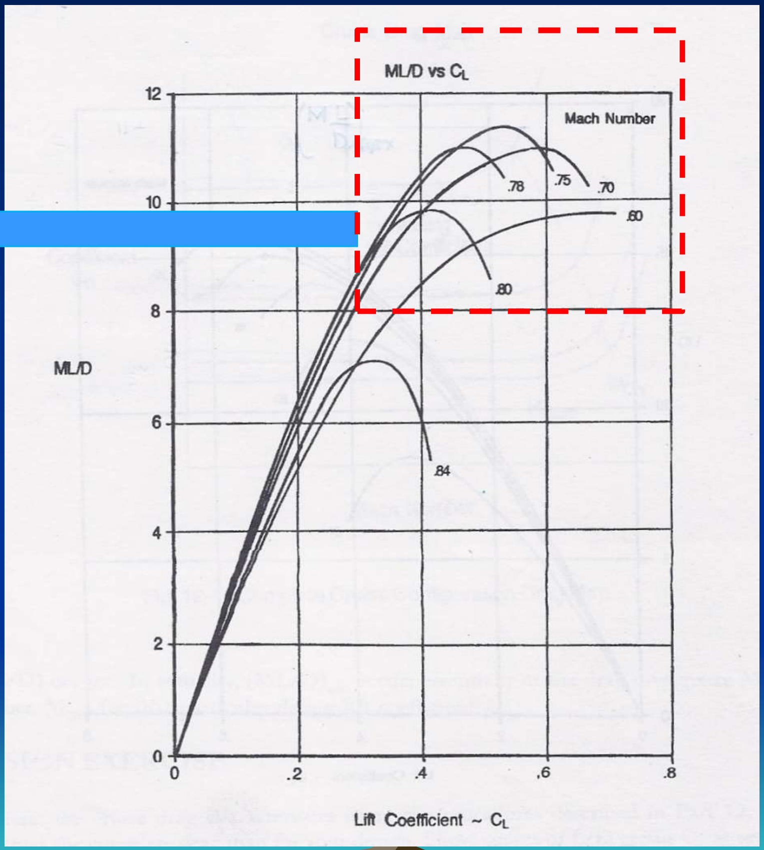
Incompressible flow region

Piano-X generates these plots

ADAC Aircraft Design & Consulting

DC-9 ML/D vs C_L

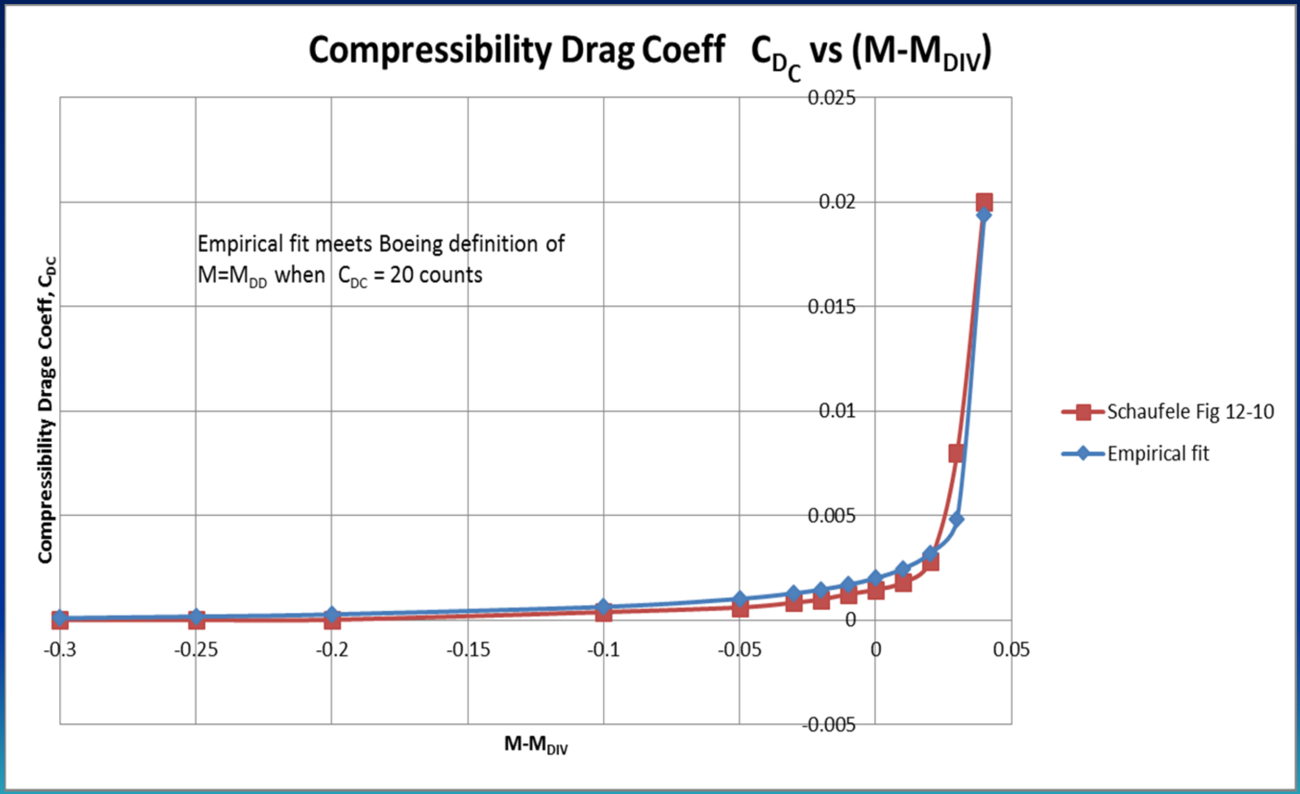




Source: Schaufele

- DC-9 airfoil is not supercritical
- $(ML/D)_{max}$ at about M = 0.75
- $(ML/D)_{max}$ = 11.5

Empirical Estimate of Drag Rise



Alternative Method of M_{DD} Estimation

Empirical Korn Equation applied to airfoil section

$$M_{DD} = \frac{k_a}{\cos\left(\Lambda_{\frac{c}{2}}\right)} - \frac{\frac{t}{c}}{\cos^2\left(\Lambda_{\frac{c}{2}}\right)} - \frac{C_l}{10\cos^3\left(\Lambda_{\frac{c}{2}}\right)} - 0.025$$

where

k_a = technology factor

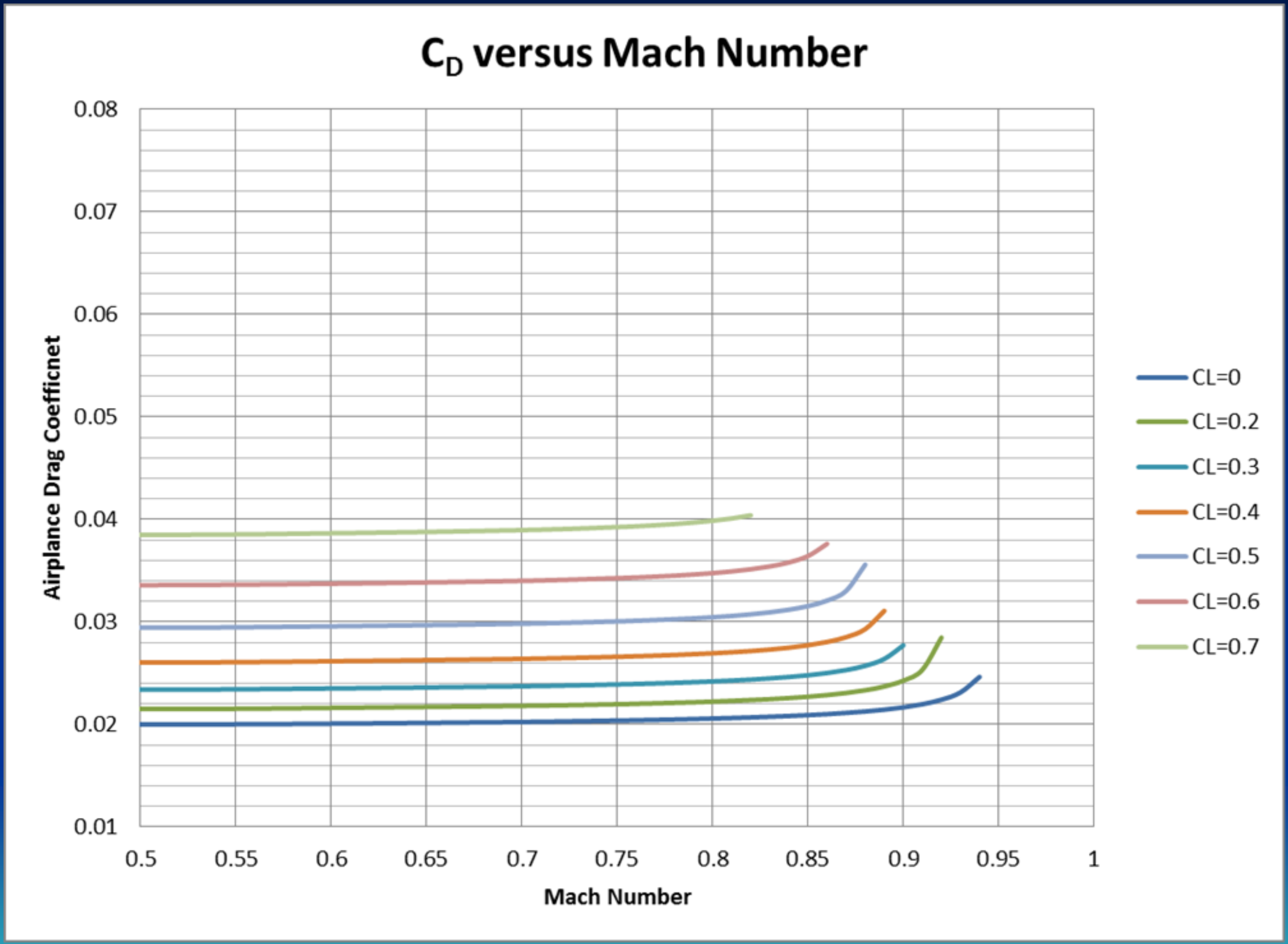
$(= 0.87$ for NACA 6-series$)$

$(= 0.95$ for supercritical airfoil$)$

For wing, divide into sections and average results

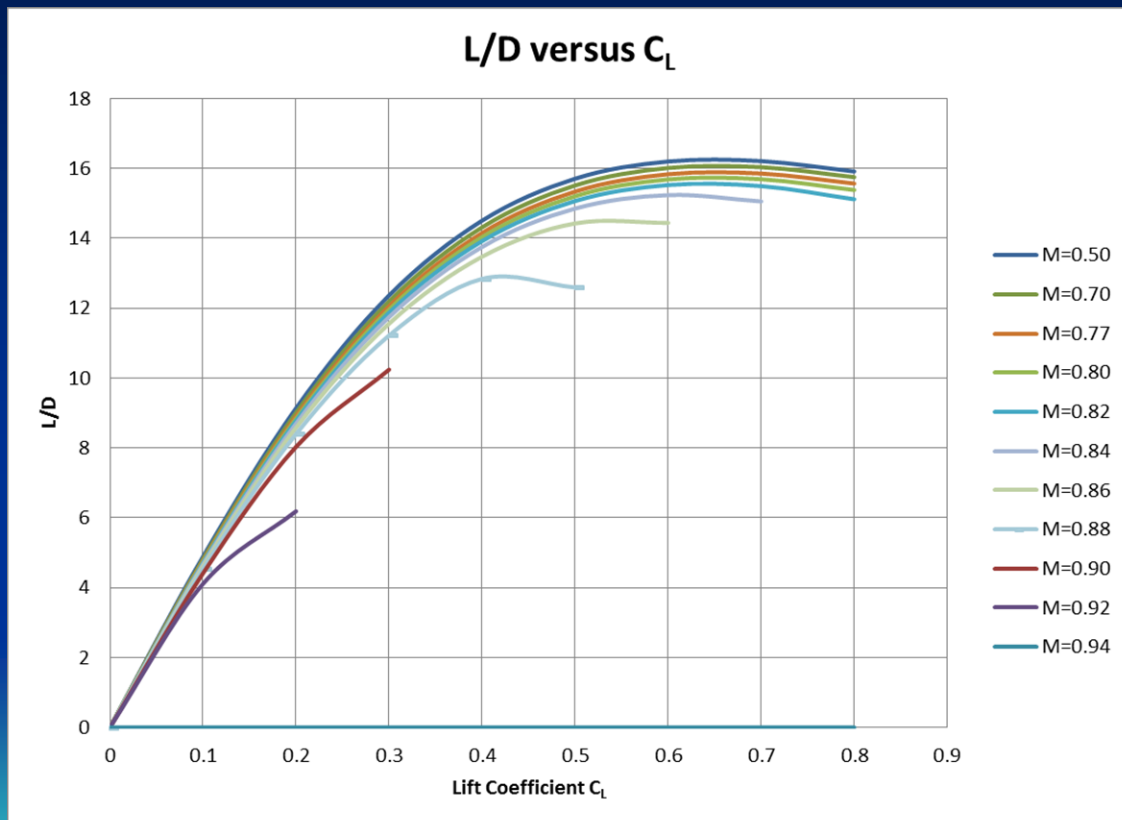
Modified from Douglas definition of $dC_D/dM = 0.10$ to Boeing definition of $\Delta C_D = 0.0020$ for this drag rise curve

For this approximation, use average values for whole wing



Source: Schaufele

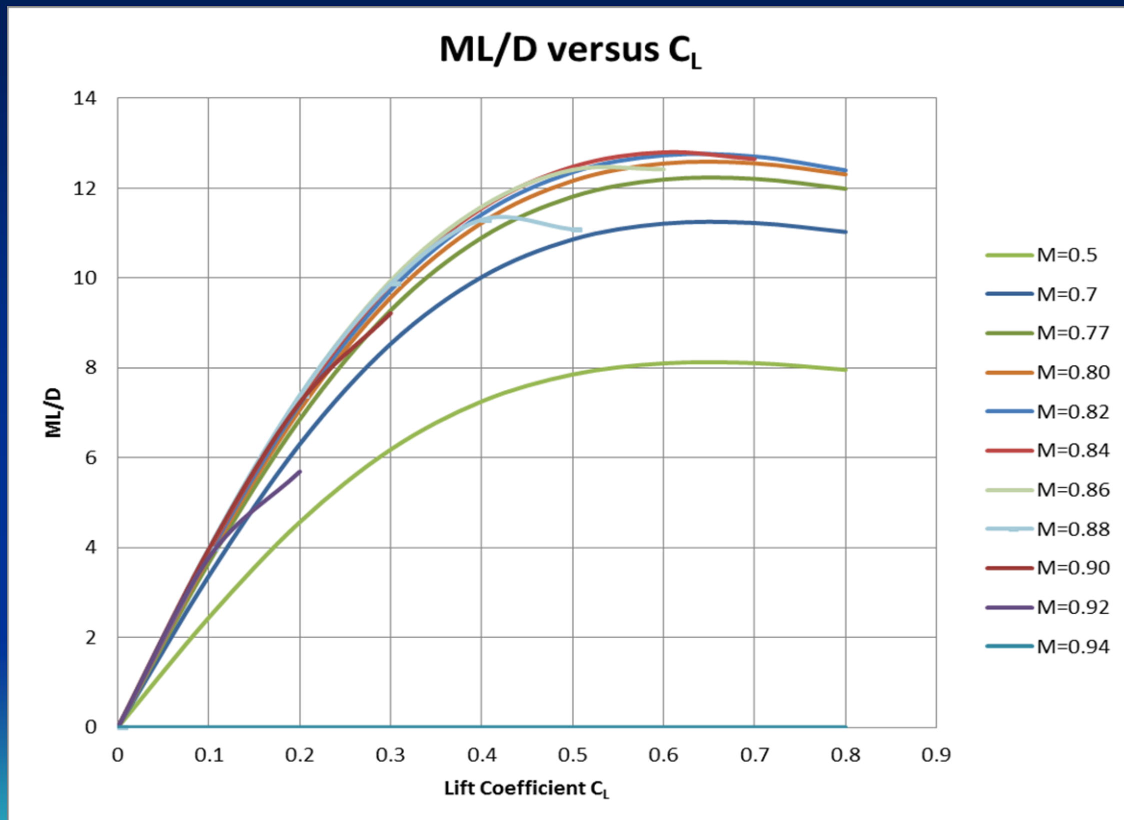
Spreadsheet Prediction for DC-10



Source: Schaufele

ADAC Aircraft Design & Consulting

Spreadsheet Prediction for DC-10



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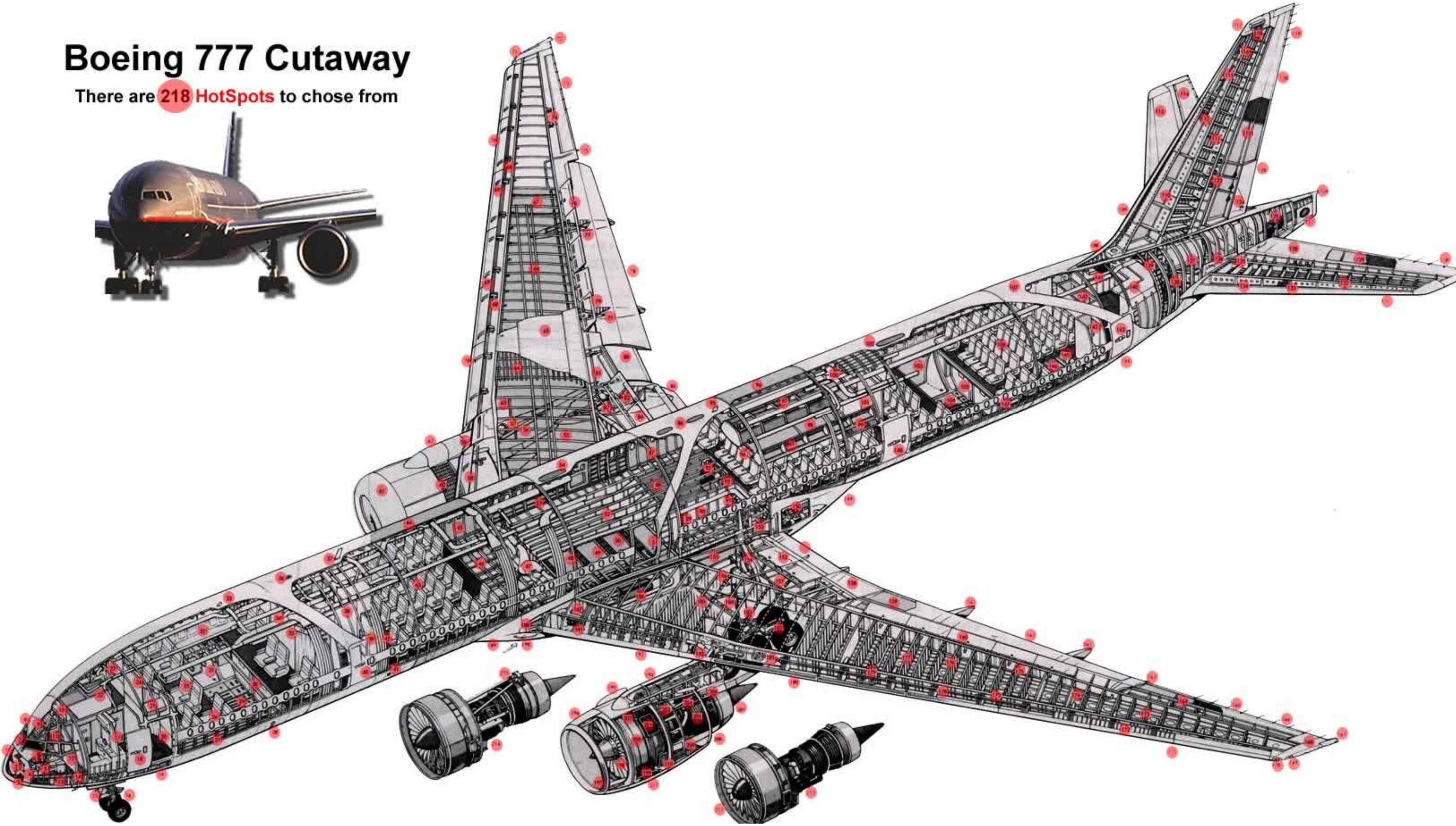
Applications of V-n Diagram

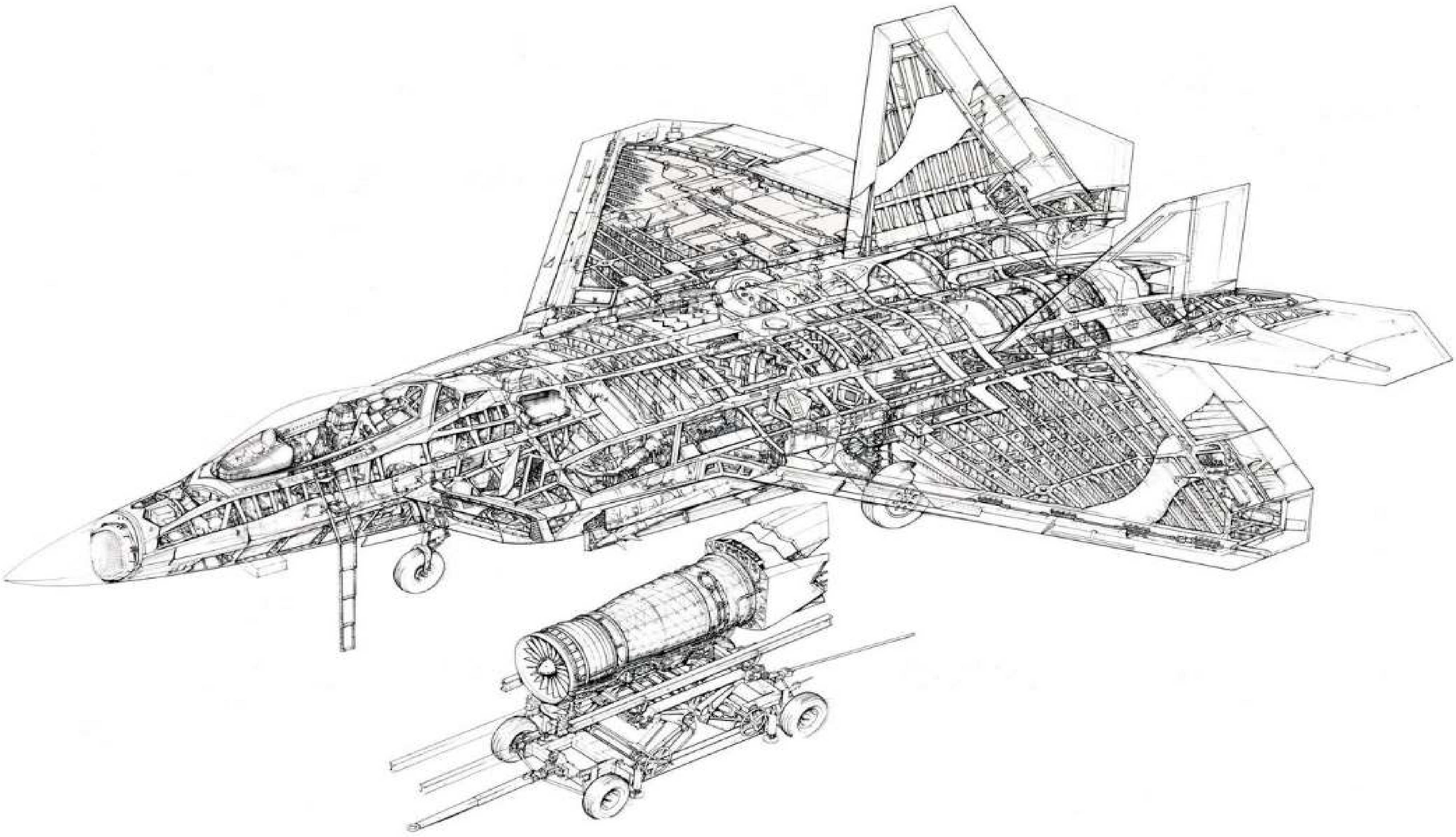
Examples

- Providing magnitude and direction of force vectors for structural designers
- Ensuring that pilots do not exceed structural limits in flight simulator

Boeing 777 Cutaway

There are 218 HotSpots to chose from





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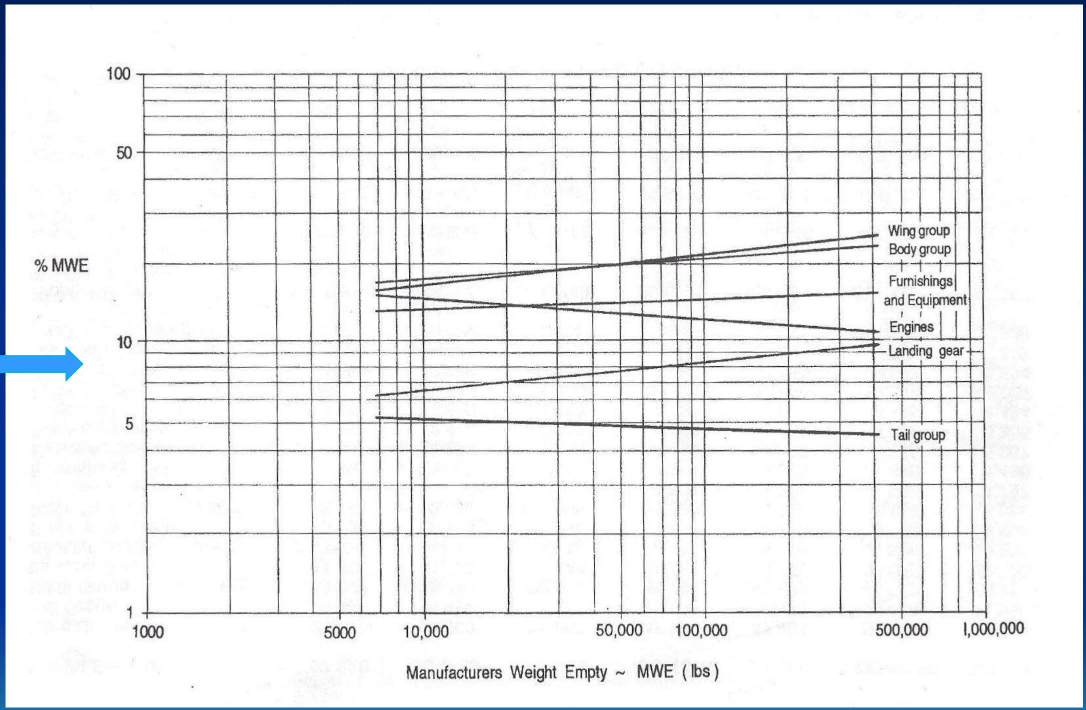
Weight and Balance

- For one-semester class, multi-variable empty weight equations (Raymer, Table 6.1),
- For balance, use group weights
- For passenger aircraft, generate potato plot
- For multi-semester class, use detailed weight buildup



Source: Jenkinson, Simpkin, Rhodes

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Two Conditions for Static Stability

First condition:

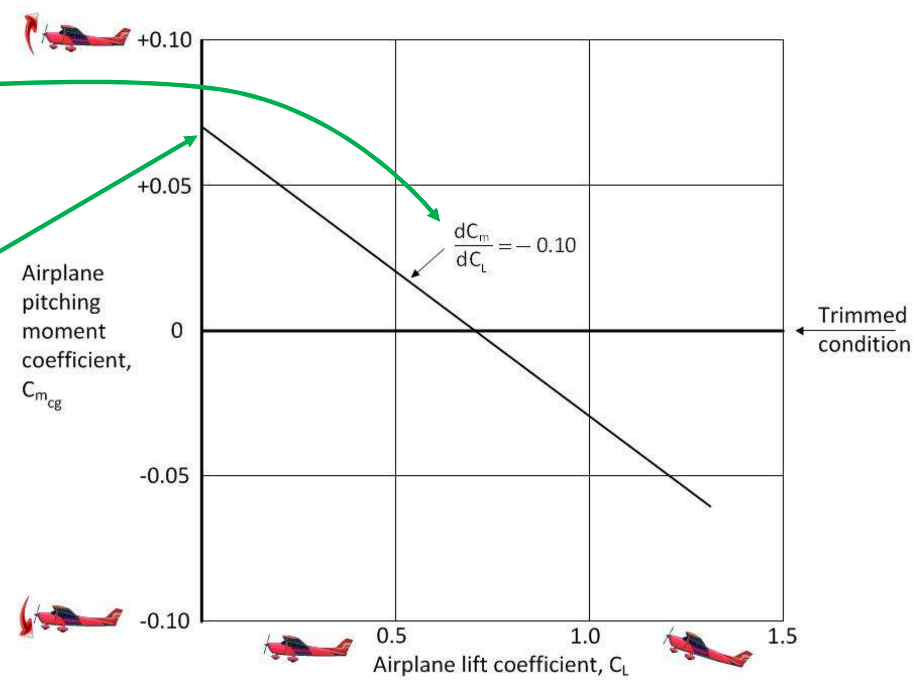
$X_{c.g.} < X_{n.p.}$

C.g. must be ahead of neutral point

Second condition:

$\left(C_{m_{cg}}\right)_{C_L = 0} > 0$

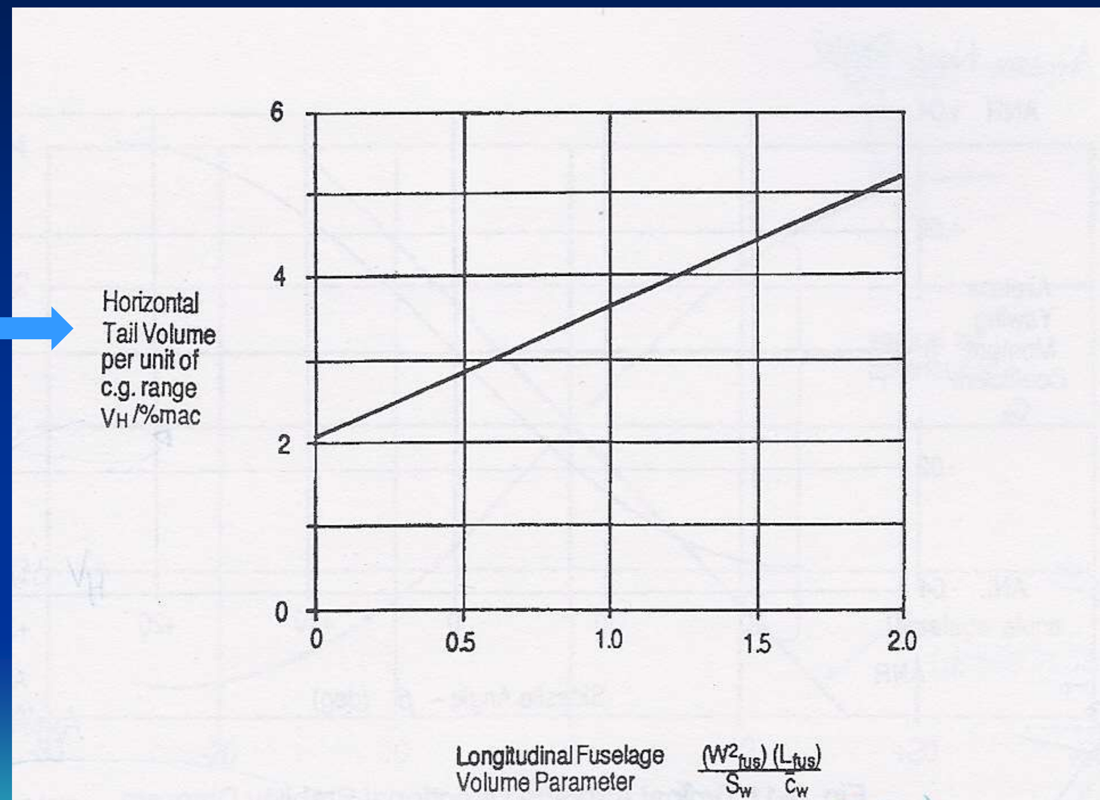
Nose up pitching moment at zero-lift condition



Estimation of $\bar{V}_{HT}$ for Transport Aircraft

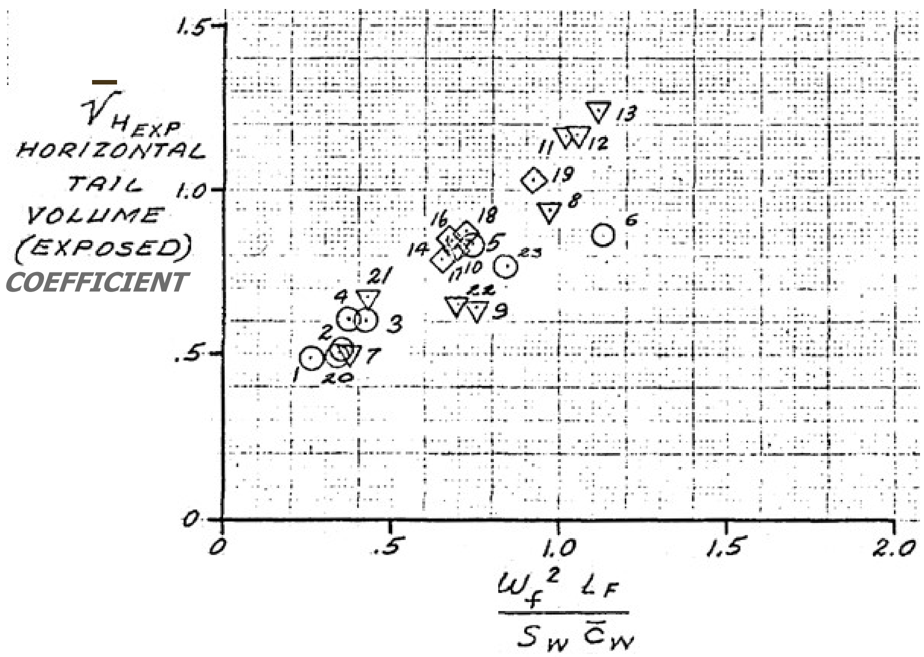
First estimate:
Use $\bar{V}_{HT}$ of comparable aircraft

Second estimate:
Use geometric correlation
W_{fuse} = fuselage width
L_{fus} = fuselage length
S_W = reference wing area
$\bar{c}_w$ = mac



Source: Schaufele

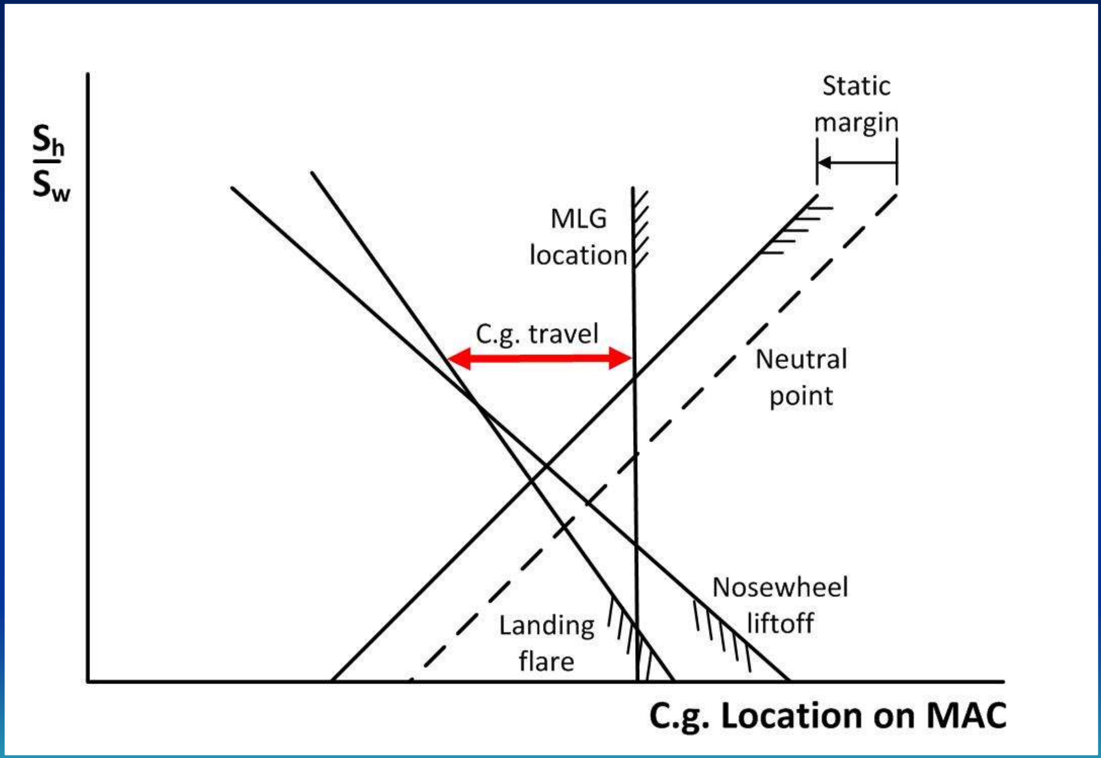
Estimation of $\bar{V}_{HT}$ for Transport Aircraft



Source:Kroo AA241

Notch Chart

- Requires analysis of stability and control requirements during different phases of flight
- Move fuselage wrt. wing so that c.g. travel fits into notch
- For multi-semester course

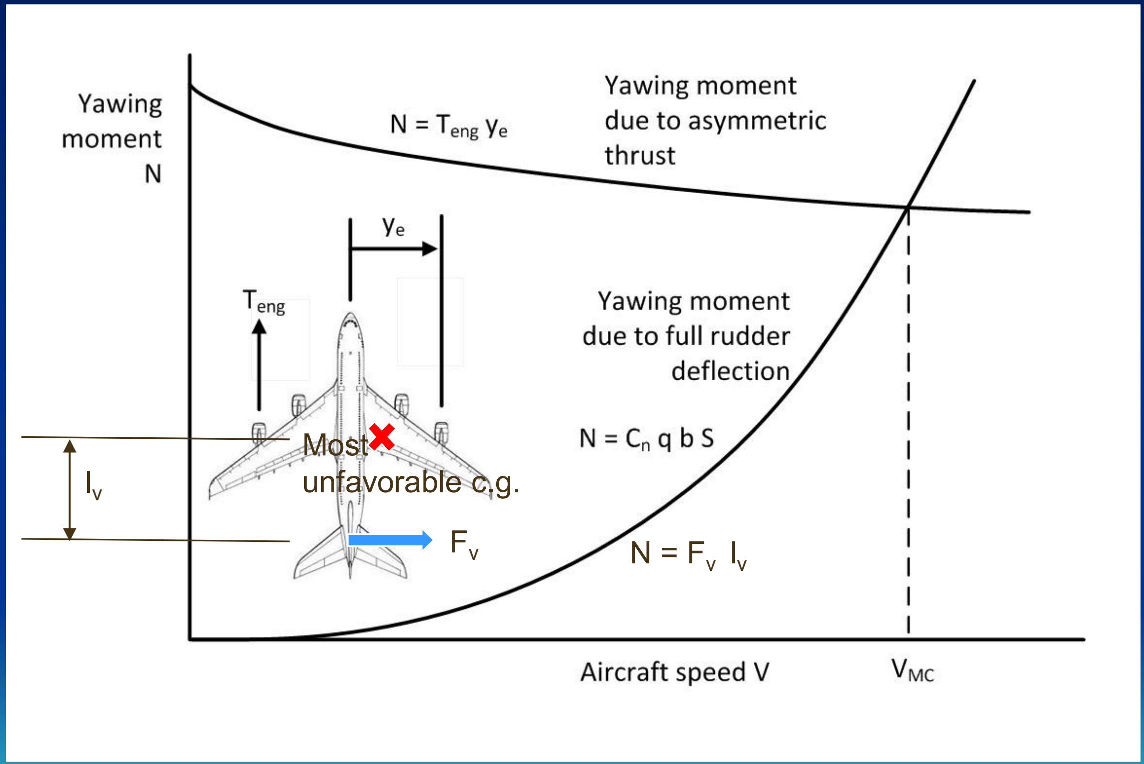


Vertical Tail Sizing Criterion (Multi-engine)

First estimate:
Use $\bar{V}_{VT}$ of comparable aircraft

Second estimate:
Use geometric correlation (as for $\bar{V}_{HT}$)

Balance engine-out yawing moment with rudder
$V_{MC} \le 1.13\ V_{SR}$ (stall speed in the takeoff condition)
(FAR 25.149(c))



FAR 25.107(e)(1)(ii)

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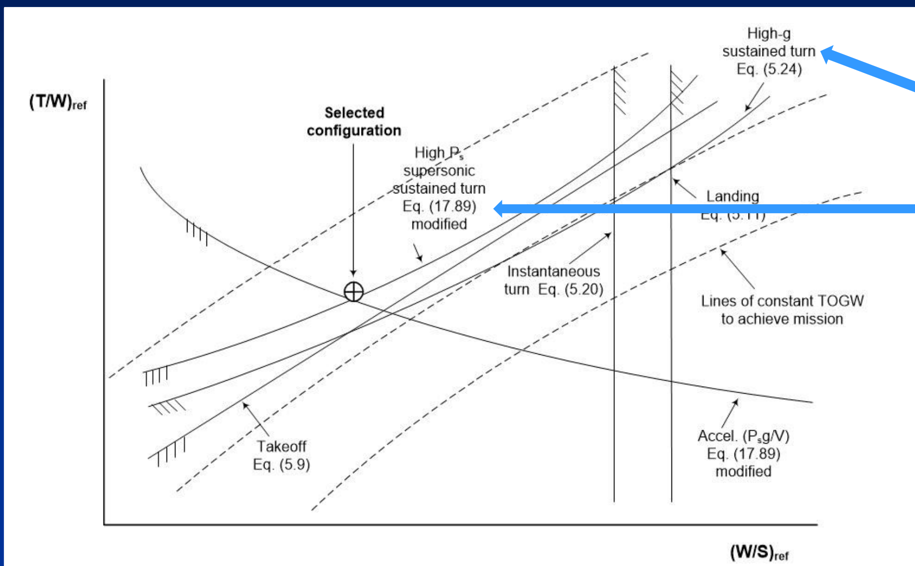
Master Performance Equation



Combine performance constraint equations into one equation

$$\frac{T}{W} = q\frac{C_{D_0}}{\left(\frac{W}{S}\right)} + \left[\left(\dot{\psi}\frac{V}{g}\right)^2 + 1\right]\frac{K}{q}\left(\frac{W}{S}\right) + \frac{P_s}{V}$$

Turn at defined $\dot{\psi}$ Climb or accelerate

Assumption is made that C_{D_0} is not a fn. of $\frac{W}{S}$

For multi-semester or graduate course

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Participate in Design-Build-Fly Competition

- AIAA DBF (www.aiaadbf.org). Respond to RFP with stated payload-range and other operational requirements
  - Proposal (submit in Dec. for contest downselect)
  - Design Report
  - Contest Flyoff (mid April, alternating between Wichita, KS, and Tucson, AZ)

2014 Cal State Long Beach team competing in AIAA DBF Competition

Participate in Design-Build-Fly Competition

- SAE Aero Design (http://students.sae.org/cds/aerodesign/) Respond to RFP with stated payload-range and other operational requirements
  - Design Presentation
  - Contest Flyoff (either Fort Worth, TX, or Van Nuys, CA)

Source: scienceinpoland.pap.pl

Source: www.youtube.com

The End

For more information visit
www.adac.aero

Boneyard

Primary Conceptual Design Responsibilities

- Aircraft layout
- TOGW
- T/W and W/S

Design refinement requires closer co-ordination with technical disciples

Primary Conceptual Design Responsibilities

- Aircraft layout
- TOGW
- T/W and W/S

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